Voltage Quality and Power Quality Factor Improvement using Active Power Line Conditioner

A Thesis Submitted in Partial Fulfilment of the
Requirements for the Award of the Degree of

MASTER OF TECHNOLOGY

in

Electrical Engineering

by

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Department of Electrical Engineering
National Institute of Technology - Rourkela
2012-2014

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ABSTRACT

This project describes an improvement method of power quality using shunt active power line conditioner (APLC) for a distorted three phase supply system feeding three phase unbalanced non-linear load. A control algorithm is presented for an APLC to compensate harmonics and unbalance factor. Sensing load currents, dc bus voltages compute reference currents of APLC. APLC driving signals are produced with the reference signals via a hysteresis band current controller. The case of distorted supply voltage condition has been considered. The p-q theory based active power line conditioner degrades in case of non-ideal source voltage condition. The use of self-tuning filter (STF) is proposed in order to improve the harmonic suppression efficiency of APLC. MATLAB/simulink power system toolbox is used to simulate the proposed system. The proposed method restricts both THD and unbalance factor of input currents and a power quality factor is designated which integrally reflects the two quality aspects (i.e., harmonic and unbalance factor) before and after compensation. Power quality factor improvement with the proposed shunt APLC has been verified by the simulation results.

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Dedicated

To

My beloved Parents

DEPARTMENT OF ELECTRICAL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

ORISSA, INDIA-769008

CERTIFICATE

This is to certify that the thesis entitled **"Voltage Quality and Power Quality Factor Improvement using Active Power Line Conditioner"**, submitted by **Mr. MARAVATHU NAGARJUNA** in partial fulfillment of the requirements for the award of **Master of Technology in Electrical Engineering** with specialization in "**Industrial Electronics**" at National Institute of Technology, Rourkela. A Bona fide record of research work carried out by him under my supervision and guidance.The candidate has fulfilled all the prescribed requirements.The Thesis which is based on candidates own work, has not submitted elsewhere for a degree/diploma.

In my opinion, the thesis is of standard required for the award of a master of technology degree in Electrical Engineering.

.

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CHAPTER-1

INTRODUCTION

Literature review

Research motivation

Thesis objectives

Organization of thesis

INTRODUCTION

Electrical energy is the most efficient and popular form of energy and the modern society is heavily dependent on the electric supply. The life cannot be imagined without the supply of electricity. At the same time the quality of the electric power supplied is also very important for the efficient functioning of the end user equipment.

The term power quality became most prominent in the power sector and both the electric power supply company and the end users are concerned about it. The quality of power delivered to the consumers depends on the voltage and frequency ranges of the power. If there is any deviation in the voltage and frequency of the electric power delivered from that of the standard values then the quality of power delivered is affected.

Now-a-days with the advancement in technology there is a drastic improvement in the semi-conductor devices. With this development and advantages, the semi-conductor devices got a permanent place in the power sector helping to ease the control of overall system. Moreover, most of the loads are also semi-conductor based equipment. But the semi-conductor devices are non-linear in nature and draws non-linear current from the source. And also the semi-conductor devices are involved in power conversion, which is either AC to DC or from DC to AC. This power conversion contains lot of switching operations which may introduce discontinuity in the current. Due to this discontinuity and non-linearity, harmonics are present which affect the power quality delivered to the end user. In order to maintain the power quality delivered, the harmonics should be filtered out. Thus, a device named *Filter* is used which serves this purpose.

There are many filter topologies in the literature like- active, passive and hybrid. In this project the use of hybrid power filters for the improvement of electric power quality is studied and analyzed.

1.1 LITERATURE REVIEW OF ACTIVE POWER FILTER:

Harmonics in Power System Due to Non-Linear Loads:

The literature study for the thesis work starts with the location of the harmonics emerging because of the utilization of non-linear loads. The primary wellsprings of harmonic currents and voltages are because of control and energy transformation systems included in the power electronic devices, for example, chopper, cyclo-converter, rectifier and so forth. The harmonic sources are energy transformation devices such as power factor improvement and voltage controller devices of motor, traction and power converters, high-voltage direct-current power converters, battery-charging systems, wind and solar-powered dc/ac converters, static-var compensators, direct energy devices-fuel cells, control of heating elements storage, batteries which require dc/ac power converters [1]. The harmonic currents and voltages were measured utilizing an element indicator analyzer by M. Etezadi-Amoli, and plotted at for diverse substations [2]. Because of utilization of non-linear loads like chopper, rectifier and so forth the load current gets contorted, which is clarified pleasantly by Robert considering harmonic study [3].

Brief Introduction to Active Power Filter:

To lessen the harmonics expectedly inactive L–C channels were utilized and additionally capacitors were utilized to enhance the power factor of the ac loads. At the same time the aloof channels have a few drawbacks like settled recompense, vast size and reverberation issue. To relieve the harmonics issue, numerous exploration work advancement are created on the active power (APF) channels or active power line conditioners [4-5]

Various Topology of Active Power Filter:

APLC's are essentially arranged into two sorts, specifically, single stage (2-wire association), three-stage (3-wire and 4-wire association) arrangements to meet the necessities of the nonlinear loads in the dissemination systems. Single-stage loads, for example, local lights, TVs, ventilation systems, and laser printers carry on as nonlinear loads and reason harmonics in the power framework [6]. Numerous setups, for example, the active arrangement channel [7], active shunt channel [8-9], and blending of shunt and arrangement channel has been produced [10]. The aforementioned APLC's either focused around a current source inverter (CSI) with inductive energy storage or voltage source inverter (VSI) with capacitive energy storage devices.

Control methodss used for Active Power Filter:

Planning a suitable controller for an APF is exceptionally vital. A number control methodologies, for example, prompt reactive power hypothesis at first created by Akagi et al. [11], synchronous edge d–q hypothesis [12], synchronous identification strategy

[13], score channel and fluffy rationale controller [32] system are utilized within the advancement of three-stage AFs and the entryway beats are created by current control method like sinusoidal beat width regulation (SPWM), triangular PWM, hysteresis current control procedure [14].

1.2 RESEARCH MOTIVATION

1.2.1 Power Quality Problems:

Amongst the power quality problems, the supply interruption is, undisputedly, the most severe, since it affects all equipments connected to the electrical grid. However other problems, as the described below and illustrated in Figure 2a to 2i, beyond of leading to some equipments malfunction, can also damage them:

- ***Harmonic distortion***: when non-linear loads are connected to the electrical grid, the current that flows through the lines contains harmonics, and the resulting voltage drops caused by the harmonics on the lines impedances causes distortion on the feeding voltages.

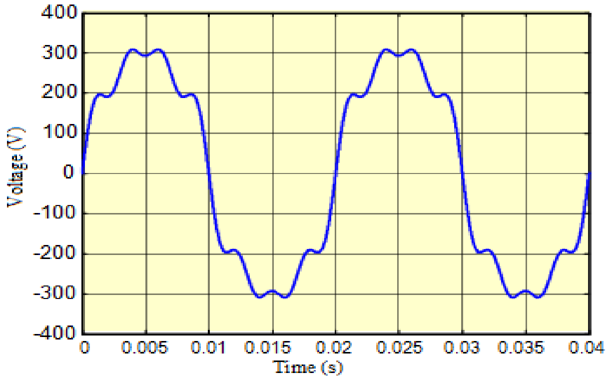


Figure 1.1 - a) Harmonic distortion

- ***Noise*** (electromagnetic interference): corresponds to high frequency electromagnetic noise, which can, for instance, be produced bythe fast switching of electronic power converters.

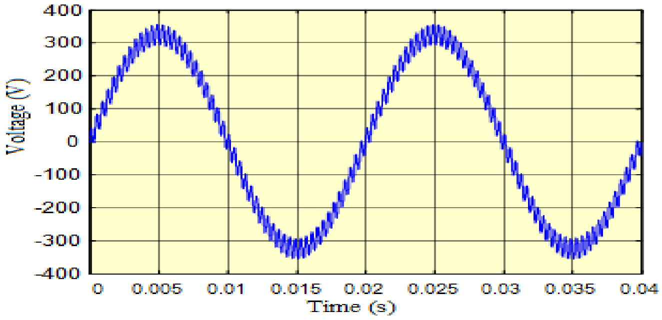


Figure 1.1 - b) Noise (electromagnetic interference)

- ***Inter-harmonics***: appear with the presence of current components that are not related to the fundamental frequency. These components can be produced by arc furnaces or by cyclo-converters (equipments that, being fed at 50 HZ, allow to synthesize output voltages and currents with inferior frequency).

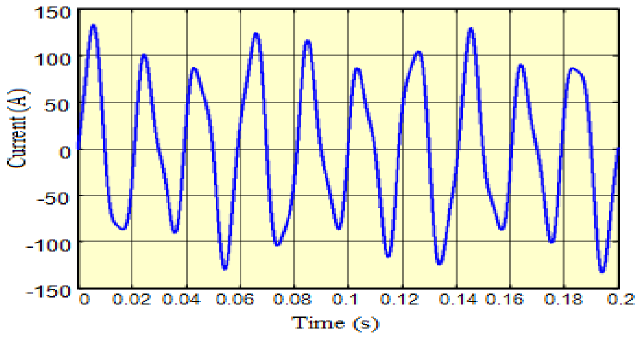


Figure 1.1 - c) Inter-harmonics

- ***Momentary interruption***: occurs, for instance, when the electrical system has automatic reset circuit breakers, that opens when a fault occurs, closing automatically after some milliseconds (and is kept closed if the short-circuit is extinguished).

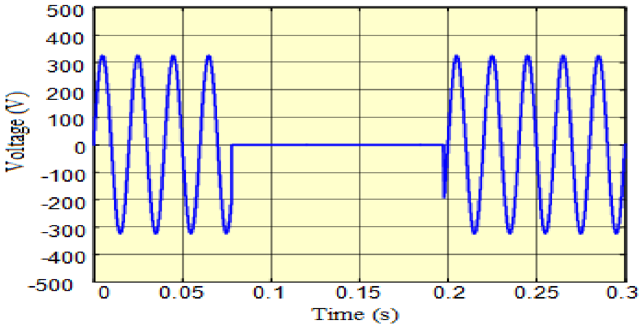


Figure1.1 - d) Momentary interruption

- ***Voltage sag***: can be caused, for instance, by a momentary short-circuit at another branch of the same electrical system, which is eliminated after some milliseconds by the opening of the branch circuit breaker.

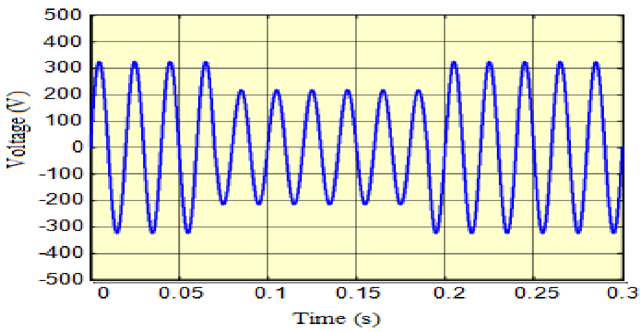


Figure1.1 - e) Voltage sag

- ***Voltage swell***: can be caused, amongst other cases, by fault situations or by commutation operations of equipments connected to the electrical grid.

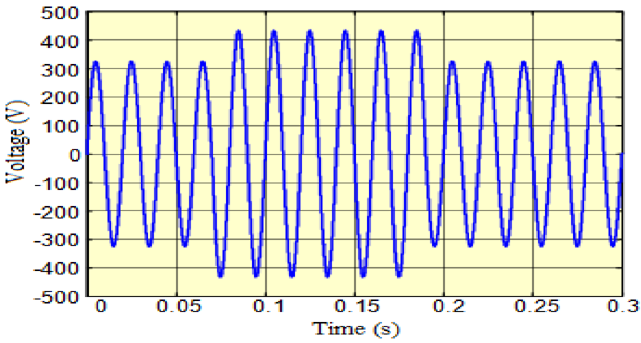


Figure1.1 - f) Voltage swell

- ***Flicker***: it happens due to intermittent variations of certain loads, causing voltage fluctuations (which results, for instance, in oscillations on electric light intensity).

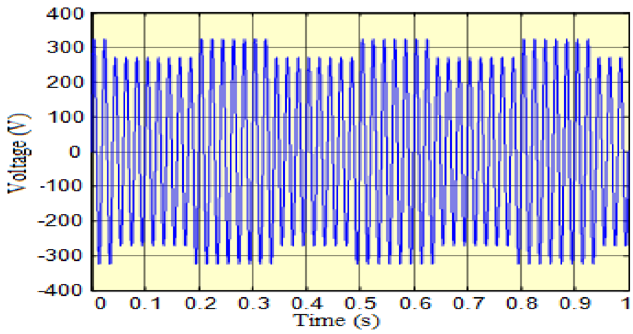


Figure1.1- g) Flicker

- ***Notches***: Consist in small periodic cuts on the voltage waveform, which result from voltage drops on the line inductances of the electrical system. These occur due to loads which consume currents with abrupt periodical variations (like rectifiers with capacitive or inductive filter).

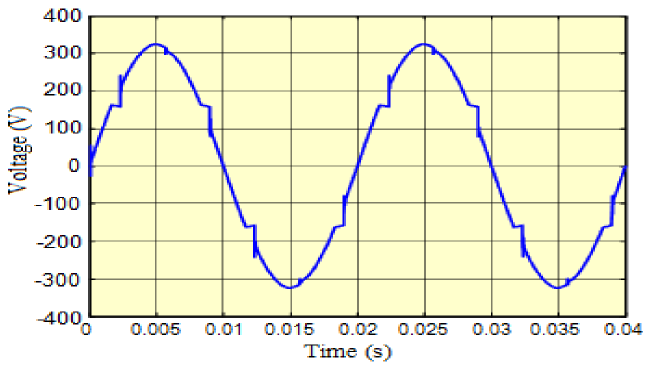


Figure1.1 - h) Notches

- ***Transients***: occur as a result of transitory phenomena, such as capacitor bank switching or atmospheric discharges.

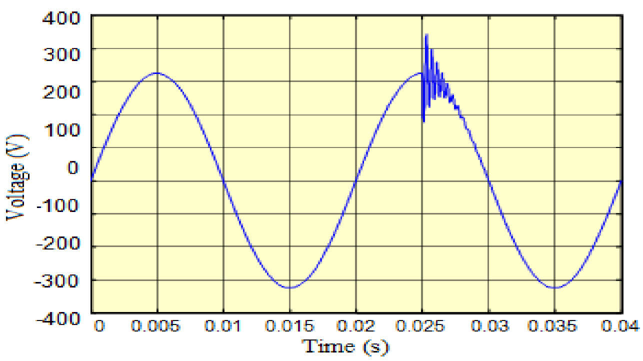


Figure1.1- i) Transients

Harmonic "Pollution" Causes:

The vast majority of the problems that occur on electrical systems have its origins on the excessive distortion of the currents or voltages near the final consumer. The main cause for this phenomena, which can be regarded has a sort of electromagnetic environment pollution, is due to the growth of the usage of electronic equipment fed by the electrical grid, such as computers, printers, television sets, electronic ballasts for gas-discharge lamps, electronic controllers for different varieties of industrial loads, etc. Almost every electronic equipments, single-phase or three phase, embodies a rectifier circuit at its entrance, followed by a commuted converter of the type DC-DC or DC-AC. One of the most usual rectifiers for low-power equipments is the single-phase full wave rectifier with capacitive filter, which has a highly distorted current consumption, as it can be seen on figures 3a and 3b. The current's high harmonic content distorts the voltage on the loads due to the voltage drops in the electrical systems impedances. Phase fired controllers, widely used to control power consumption of heating systems and to adjust luminous intensity of lamps (dimmers), also consume currents with substantial harmonic content and with high-frequency electromagnetic interference. Even the ordinary fluorescent lamps contribute significantly for the presence of harmonics in the electrical grid, due to the non-linear behavior of the electrical discharges on the gaseous environment, and also to the ballast's magnetic circuit, that can operate on the saturation region.

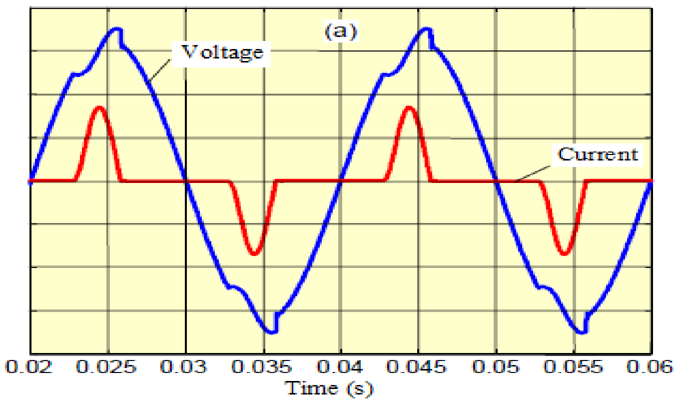


Figure 1.2 - a) Voltage and current in a single phase rectifier with a capacitive filter

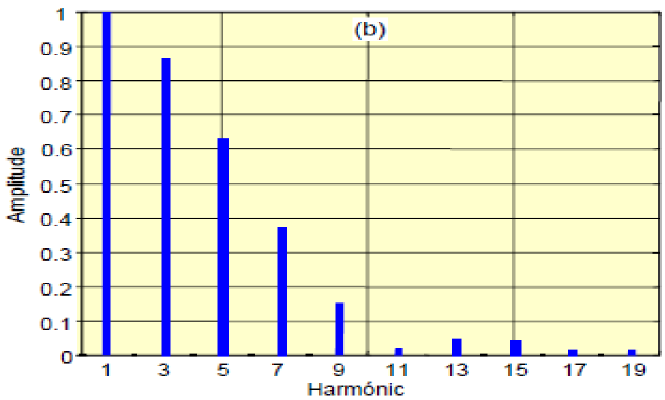


Figure 1.2 - b) Harmonic of the current in input

Harmonic "Pollution" Effects:

Besides wave shape distortion, presence of harmonics on energy distribution lines causes problems on equipments & components of electrical system, namely:

- Increased losses (heating), saturation, resonances, windings vibration and life span reduction of transformers.
- Heating, pulsed torque, audible noise and life span reduction of rotating electrical machines;
- Undue firing of power semiconductors in controlled rectifiers and voltage regulators;
- Operation problems on protection relays, circuit breakers and fuses; Increased losses on the electrical conductors;
- Considerable increase of the capacitor's thermal dissipation, leading to dielectric deterioration;
- Life span reduction of lamps and luminous intensity fluctuation (flicker – when sub-harmonics occur);
- Errors on the energy meters and other measurement devices;
- Electromagnetic interference in communication equipments;
- Malfunction or operation flaws in electronic equipment connected to the electrical grid, such as computers, programmable logic controllers (PLCs), control systems commanded by microcontrollers, etc. (these devices often control fabrication processes).

Real cases of problems caused by harmonics:

A new computation system was installed in an insurance company building. Once the system was turned on, the main circuit breaker opened, putting all system off-line. After several verifications, the engineers discovered that the interruption had been cause by an excessive value of current in the neutral wire of the three-phase system. Despite the system being balanced, the neutral wire current had a value equal to 65% of the value of phase current, which led to the triggering of the circuit-breaker, since the neutral wire current relay was set to 50% of the value of phase current. It should be high lighted that in a balanced three-phase system, the neutral current must be equal to zero. However, when the current is distorted, contrarily to what normally occurs, the current harmonics multiple of three are summed in the neutral wire, instead of canceling each other. Studies demonstrate that neutral currents have increased in commercial buildings. This is due to the growing use of electronic equipment, such as computers, printers, copiers, faxes, etc. Those equipments use single-phase rectifier at their entrance, which consume 3rd order current harmonics, such as the 3rd, 9th and 15th harmonics. In order to avoid neutral wire heating problems, these must be oversized, or, even better, the 3rd order harmonics must be compensated. In another documented case, an electrical power distribution company reported a 300kVA transformer break down, whose load did not exceed its rated apparent power. The transformer was replaced by an identical one, but it started to show the same problems shortly after. These transformer's loads mainly consisted of electronic variable speed drives for electric motors, which current consumption has a large harmonic content. Nowadays, in order to avoid transformers break down, or reduced life span, it's important to know the harmonic distortion of the currents delivered to the load by them. In function of that value, it will be applied to the transformer a power derrating factor (factor K). This means, in function of the harmonic distortion value, the rated power value of the transformer is reduced.

1.2.2 Power Quality Problems Solutions:

The solution for some of the more traditional power quality problems can be achieved by using the following devices or equipments:

- The UPSs (Uninterruptable Power Supplies) or emergency generators are the only solution for long interruptions in the electrical power supply;
- Transient Voltage Surge Suppressors guarantee protection against transient phenomena which cause voltage spikes in the lines;
- The electromagnetic interference filters guarantee that polluting equipment does not propagate the high frequency noise to the electrical grid;
- Isolation transformers with electrostatic shield offer not only galvanic isolation, but also avoid the propagation of voltage spikes to the secondary winding.

- Ferro-resonant transformers ensure voltage regulation, as well as solve overvoltage problems.
- Voltage regulation can also be ensured by means of transformers with several outputs, associated with a commutation electronic scheme by thyristors.

Solution for harmonics problems:

Next, there will be presents some traditional (passive filtering) and modern (active filtering) solutions for the harmonic problem in equipments and electrical systems.

Low Power (Single-phase systems):

The simplest passive filter consists of an inductor series connected to the entrance of the "polluting equipment", which often is a rectifier with capacitive filter output (Figure 1.3a). This is a reliable and low cost solution. However, the inductor is bulky and heavy (due to the iron on its magnetic circuit), which practically limits this solution to low power equipments (less than 600 VA). A very frequent change made in the project of single-phase electronic equipment, in order to significantly reduce the produced harmonics, is to use a step-up DC-DC converter after de Rectifier Bridge (Figure 1.3b). That circuit, when correctly controlled, allows that the current consumed by the equipment is virtually sinusoidal, and it can be used up to the power usually available in single-phase outlets (about 3 KVA). Load

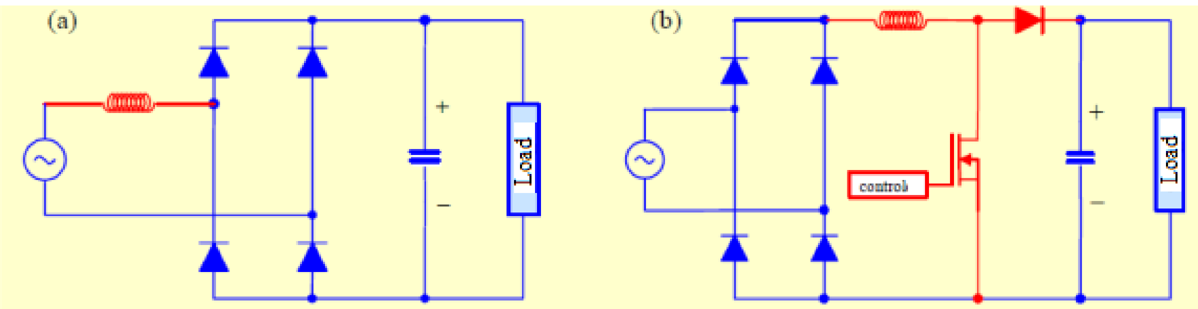


Figure 1.3 - Solutions to reduce the harmonics of the current in the input of the equipments: a) Series inductance; b) Step-up converter

- ***Medium and High Power:***

For a long time, the electrical power distribution companies only have been imposing reactive power limits to the industrial consumers. The normally adopted solution by the industry consisted on the use of power factor correction capacitors banks. More recently, the problems related to the current harmonics flowing through the electrical grid, have forced many industrial consumers to apply harmonic reduction techniques based on passive filters. However, this solution presents several disadvantages, namely: the passive filters only filter the frequency for which they were previously tuned; they often need to be over dimensioned, since it is not possible to limit their operation to a specific load they end up absorbing harmonics from the surrounding electrical system; resonance phenomena may occur between the filter and other loads connected to the grid with unforeseeable results; sizing of passive filters must be coordinated with the load's needs of reactive power and is difficult to do so, to avoid that the pair filter-load operate with capacitive power factor in some conditions. To overcome these disadvantages, there have recently been some efforts to develop active power filters.

- ***Shunt Active Filter:***

The Shunt Power Active Filter has the function to compensate the load currents harmonics, allowing also compensating the reactive power (power factor correction). It also allows balancing the currents on the three phases (eliminating neutral wire current even when 3rd harmonic exists). As it is shown on Figure 1.3, as result of the shunt active filter operation, the lines current becomes sinusoidal, and its amplitude drops, reducing losses on the wires and avoiding voltage distortion on the loads. Figure 1.4 presents the electrical scheme of a three-phase shunt active filter. The filter is basically composed by an inverter, which produces the compensation currents, and by its controller.

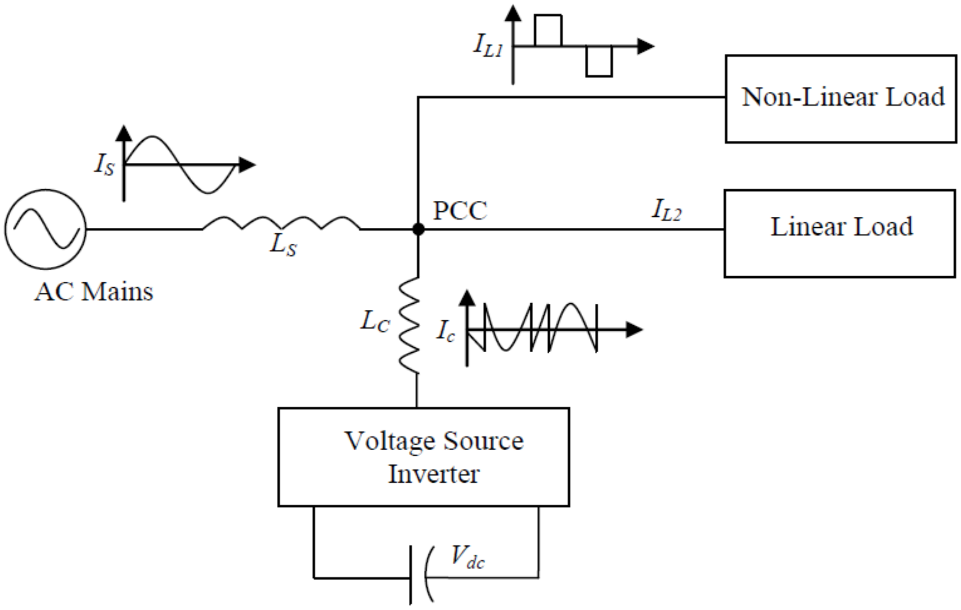


Figure 1.4 Shunt Active Filter

1.3 THESIS OBJECTIVES:

1.1 THESIS OBJECTIVES:

The principle objective of this work is

- To contrast the requisite performance of a shunt APLC to indemnify unbalanced non-linear loads with unbalances and current harmonics under non-ideal supply voltage conditions.

- To analyse the supply-current unbalances and supply-current distortion, THD, after and before the compensation.

- To calculate the power quality factor considering unbalances and harmonics of the supply current after and before the active compensation.

1.4 ORGANIZATION OF THESIS:

The whole thesis is organized into six chapters including introduction and each chapter is summarized below.

In Chapter 2, the APLC's conceivable outcomes to enhance the electrical power quality are indicated.

In Chapter 3, is exhibited the APLC power stage. The distinct topologies and its execution are presented.

Chapter 4 deals with the Voltage quality factor, Power quality factor and distinct quality aspects measured.

In Chapter 5, The principle shunt APF control strategies to mitigate nonlinear loads are detailed.

In Chapter 6, The essential principles to pick the passive components of a converter system association are exhibited. These are carried out with the help of MATLAB® and Simulink®.

Chapter-2

POWER QUALITY FACTOR FOR ELECTRICAL NETWORKS

Voltage and Current Harmonics

Voltage and Current Unbalance

Power Quality Factor

Voltage Quality Factor

Power-quality Factor for Electrical Networks

A general integral assessment of the power-transfer quality of a three-phase network by means of a new indicator designated the power-quality factor (PQF) is suggested using the Fourier techniques.

The *PQF* considers various quality aspects (*QA*) notably the current and voltage harmonic levels, the phase displacements between corresponding phase voltages and currents at the fundamental frequency, and the degree of unbalance in the different phase voltages and currents.

The different *QAs* are distinctly measured so that, if necessary, the specific quality aspect that needs correction can be readily identified.

Prominent voltage quality aspects considered in the *VQF* are the power-system-frequency variations, the voltage harmonic levels and the degree of unbalance in the different phases at the fundamental frequency.

A network supplying balanced sinusoidal voltages with no frequency variations would yield a *VQF* of unity. A high level of power quality is understood as a low level of disturbances; agreement on acceptable levels of disturbances is needed.

Under steady-state conditions, three power-system parameters – frequency, waveform distortion, and symmetry – can serve as frames of reference to classify the disturbances according to their impact on the quality of the available power. The phase displacement between voltage and current has been added as another important quality aspect.

2.1 Voltage and Current Harmonics

SOURCES OF CURRENT HARMONICS

Among the sources of harmonic voltages and currents in power systems three groups of equipment can be distinguished:

• Magnetic core equipment, like transformers, electric motors, generators, etc.

• Arc furnaces, arc welders, high-pressure discharge lamps, etc.

• Electronic and power electronic equipment.

EFFECTS

Current effects related to the instantaneous or time-averaged current value (overheating of electric machines, capacitor fuses blowing, increased losses in transmission lines, unwanted operation of relays, etc.). Harmonics in power supply systems are the main cause of temperature rise in the equipment and shortening of in-service time. This effect attains extremely high values under conditions of resonant amplification of harmonic currents.

Voltage effects Associated with the peak, average or r.m.s. value of distorted voltage.

2.1.1 Total Current and Voltage Harmonic Distortion

The total harmonic distortion of the voltage and current VTHD and ITHD, respectively, for single-phase (or poly-phase balanced) networks have been conventionally defined as

$$\boldsymbol{VTHD^2} = \frac{\sum_{h\neq 1} V_h{}^2}{V_1{}^2} \quad , \quad \boldsymbol{ITHD^2} = \frac{\sum_{h\neq 1} I_h{}^2}{I_1{}^2} \tag{1}$$

where V and I denote rms values and 1 and h denote the fundamental and the harmonic order, respectively.

The first quality aspects $QA_1$and QA_2, are identified with the total harmonic distortions VTHD and ITHD for a three-phase unbalanced system and are given by

$$\boldsymbol{QA_1 = VTHD} = \frac{V_{eH}}{V_{e1}} \quad , \quad \boldsymbol{QA_2 = ITHD} = \frac{I_{eH}}{I_{e1}} \tag{2}$$

where V_{e1} and I_{e1} denote the fundamental equivalent phase voltage and current.

Definition of Equations (1), (2) satisfy the particular requirement that the total losses in the equivalent balanced three-phase system be equal to those in the actual system considered. The underlying assumptions are that a) the line and equipment losses for a certain frequency are proportional to either the square of the voltage or the square of the current and b) the line and equipment parameters are symmetrical.

2.2 Voltage and Current Unbalance

SOURCES

Unbalanced operating conditions in an electric power system are caused mainly by the operation of unbalanced loads.

Most low-voltage loads and certain medium-voltage ones, e.g. an electric traction motors, are single-phase appliances. Operation of such equipment in the three-phase system results in unbalanced load currents. Consequently, unsymmetrical voltage drops in individual phases of the supply system are produced, thus voltage at nodes of the network becomes unbalanced.

Three-phase loads which may introduce unbalance in the power system are arc furnaces. The disturbance results from different impedances of high-current paths of the furnace and not equal phase loads being the effect of the physical nature of the melting process, i.e. variations in the arc impedance. As arc furnaces are the devices of relatively large power (tens or even hundreds of MVA), the furnace load unbalance may result in significant voltage unbalance in the supply system.

The sources of unbalance can also be three-phase components of the transmission system, in particular overhead lines. Due to different tower geometries the conductors of individual phases are not simultaneously at the same location as each other and to earth. Following this, the line has different values of phase parameters, and also the values of a voltage loss in individual phases are different.

EFFECTS

The negative-sequence and zero-sequence currents flowing in an electric power system result in

- Additional losses of power and energy;
- Additional heating, the consequence of which is the limitation of line transmission capability for positive-sequence currents;
- Voltage unbalance at nodes of the network.

Voltage unbalance adversely affects the operation of loads. Asynchronous motors, synchronous generators and rectifiers are the most sensitive loads in this respect.

2.2.1 Unbalance Factor

As is well known, unbalanced voltages and currents in poly-phase networks affectthe quality of power transfer in many aspects, such as increased line losses for the same power-transfer level, extra rotating losses in drives and overloading of neutral conductors in four-wire distribution systems.

Applying the theory of symmetrical components, an unbalanced three-phase sinusoidal voltage system [*Va, Vb, Vc*] can be decomposed into a positive-sequence three-phase balanced system V^+, a negative-sequence system V^-, and a zero sequence system V^0 according to

$$V^+ = \frac{1}{\sqrt{3}}(V_a+aV_b+a^2V_c) \quad , \quad V^- = \frac{1}{\sqrt{3}}(V_a+a^2V_b+aV_c) \quad , V^0 = \frac{1}{\sqrt{3}}(V_a+V_b+V_c)$$

where V denotes the phasor of V and the factor $a = \exp(j2\pi/3)$. The symmetrical components of the currents $I+$, $I-$ and $I0$ at the fundamental frequency are derived similarly. The equivalent voltage can be expressed as

$$V_{e1}^{\ 2} = (V^+)^{\ 2} + (V^-)^{\ 2} + (V^0)^{\ 2}$$

Pertinent quality aspects QA_3 and QA_4 are the voltage and current unbalance factors VUF and IUF respectively defined as

$$QA_3 = VUNB = \frac{\sqrt{V_{e1}^{\ 2} - (V^+)^2}}{V_{e1}} \qquad , \qquad QA_4 = IUNB = \frac{\sqrt{I_{e1}^{\ 2} - (I^+)^2}}{I} \tag{3}$$

2.3 Definition of the Power-quality Factor

A single measurable indicator, designated the power quality factor (PQF), is suggested to integrally reflect the different power-quality aspects formulated in the last section. This is expressed as

$$PQF = \sum_i w_i(1 - QA_i) \tag{4}$$

where w_i are judiciously selected weighting factors that sum up to one and QA_i are the different quality aspects formulated

A balanced loaded network, with sinusoidal currents and voltages and zero phase displacements yield an ideal *PQF* of unity. Conversely, a low value of *PQF* would indicate a low degree of utilization of the power capacity of the source and/or a high level of harmonics and/or a high degree of unbalance between the phases.

2.4 Definition of the Voltage-quality Factor

A single measurable indicator, designated the voltage quality factor (VQF), is suggested to integrally reflect the different voltage quality aspects QA_i (i= 1, 2, 4) formulated above. This is expressed as

$$\boldsymbol{VQF = \sum_{i=1,3} w_i (1 - QA_i)} \tag{5}$$

where w_i are judiciously selected weighting factors of the voltage signal that sum up to one.

Balanced loaded networks, with sinusoidal voltages yield an ideal *VQF* of unity. Conversely, a low value of *VQF* would indicate a high level of harmonics and/or a high degree of unbalance between the phases with the contribution of each aspect being well defined and measurable.

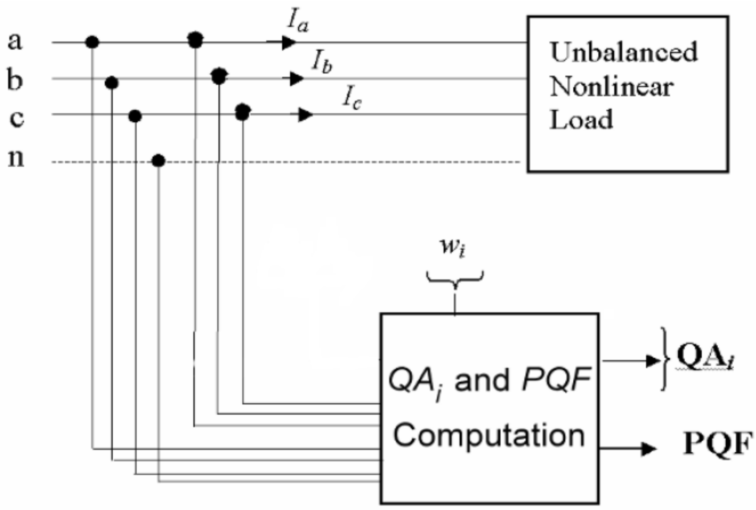


Figure 2.1 Conceptual block diagram for the measurement of the power quality factor and assessing of the different quality aspects in a three–phase supply.

CHAPTER-3

ACTIVE POWER LINE CONDITIONERS

Introduction

Power Quality and Active Power Filters

ACTIVE POWER-LINE CONDITIONERS

Nowadays, the active power filters, APFs, can be used as a practical solution to solve the problems caused by the lack of electric power quality, EPQ. The emerging technology of power-electronic devices and the new developments in digital signal processing, DSP, have made possible its practical use. These power filters can fully compensate the nonlinear loads of electrical power systems: harmonics, reactive power, unbalances, *etc.* So, they can be called active power line conditioners (APLCs). There are many configurations of APLCs, from shunt and series connection to hybrid passive-active filters. The target is to optimize the design using the advantages of each filter with the different load configurations.

In this chapter, the more common APLC configurations will be presented. The usual power blocks, the control strategy and the modulation control method will be shown. In particular, a shunt APLC design will be detailed. In this case, the goal is to inject, in parallel with the load, a compensation current to get, *e.g.*, a sinusoidal source current.

3.1 Introduction

In recent years, the rated power and the switching speeds of electronic devices (IGBTs, GTOs,...etc) have increased. On the other hand, there are new possibilities of digital signal processing (DSP boards). An old idea, active power filters, is now possible from a practical point of view. The APF concept is to use a DC/AC converter to inject currents or voltages harmonic components to cancel the load harmonic components. The more usual configuration is a shunt APF to inject into the system the current harmonics. Besides, the control strategy can include other targets to compensate the reactive power or to balance the asymmetrical load currents.

An APF can be installed in a low-voltage power system to compensate one or more loads; thus, it avoids the propagation of current harmonics along the system. The developments of power and control stages of APFs are made possible to compensate the reactive power, the negative and zero sequences. For this, a new term is used to name the APFs: active power-line conditioners, APLCs. There are shunt, series, combined shunt series APFs, and some hybrid passive and active configurations. Two usual hybrid topologies are series active-shunt passive filter, and shunt active-shunt passive filter. In the second topology, the active filter can compensate current harmonics and reactive power eventually, whereas in the first one, the active filter target is to improve the performance of the passive filter. In this case, the active filter insulates the harmonics between the source and the load.

The first APLC for harmonic compensation was installed in 1982. From this date, many high-power devices have been installed thought the world, principally in Japan. The experimental and industrial advances have improves the APLC utilities. So, from 1993, some studies on unified power quality conditioners (UPQCs) have appeared. The UPQCs integrate a combination of series and shunt active filters. The target is to compensate flickers and voltage unbalances in three phase systems, besides the reactive power, unbalanced currents or load harmonics currents. This scheme is a new step to improve the power quality in electrical installations.

The three main aspects of an active power conditioner are:

- The configuration of power converter (the scheme and the topology of converter, and the electronics device used);
- The control strategy (the calculation of APLC control reference signals);
- The control method used (how the power inverter follows the control reference, usually through the pulse width modulation of the switch device trigger signals, that is, the PWM method).

So, the design of the control strategy (according to the application), and the election and implementation of the control method are key to the APLC design.

3.2 Power Quality and Active Power Filters

The electrical power quality (EPQ) is associated with alterations and disturbances of the electrical supply that may generate electrical and electronic systems performance failure and malfunctions. In particular, the number of commercial and industrial equipment based on power electronics is increasing, which are the origin of the harmonic distortion. The traditional solutions proposed to eliminate the harmonic currents include: electrical equipment over dimensioning, three-phase transformer special connections to eliminate the third and its proportional harmonics, and the connection of passive elements, but they have more disadvantages than advantages. The technical evolution in rated power and switching speed of electronic devices, allows nowadays the application of the active power filters, APFs.

An APF is an electronic converter that produces and injects into the system the necessary harmonic components to cancel the harmonics of load current. An APF can be installed in the point of common coupling (PCC) of an AC system to compensate one or several loads. Once installed, the current harmonic circulation to the system is limited. Nowadays, APF development allows its application to compensate the reactive power, the negative sequence currents, and the harmonic currents. So, the APFs are generically named active power-line conditioners (APLC). Besides, hybrid systems with active and passive filters have been proposed, and since 1995, several studies on unified power-quality conditioners (UPQC) have appeared. The UPQCs include series and shunt active filters in the same module. The general targets are the correction of flicker and three-phase voltage unbalances, and the compensation of reactive power, harmonic currents and current unbalances. This is the next step to correct the power quality with active power conditioners.

The parameters to define an APLC are the circuit configuration of a power converter (its scheme, the power inverter topology, and the electronic devices used), the control method (PWM modulation), and the control strategy (the way to obtain the reference signal). In this section, the current APLC configurations and the basic performance will be presented.

3.2.1 Distribution Static Compensator, DSTATCOM

The more usual APLC configuration is the shunt or parallel connection. Figure 3.1(i) shows the basic scheme of the connection, where an IGBT switching device represents the APLC power block. The loads with current harmonics can be compensated by this APLC configuration. A typical example of a current-source load is a rectifier with an inductive branch in dc side.

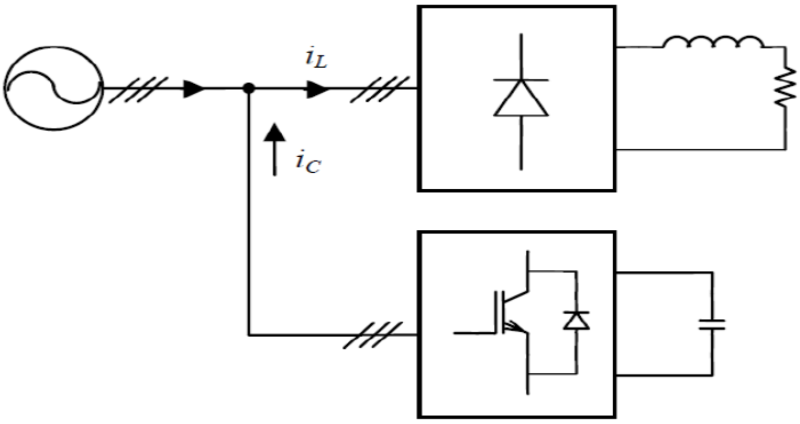


Figure 3.1.(i)A shunt APLC scheme

Figure 3.1(ii) shows the basic performance of a shunt APLC. The general aim is that the shunt APLC will inject into the system a compensation current, i_C, to cancel the harmonic component of the load current, i_L. The source current i_S becomes sinusoidal after the compensation.

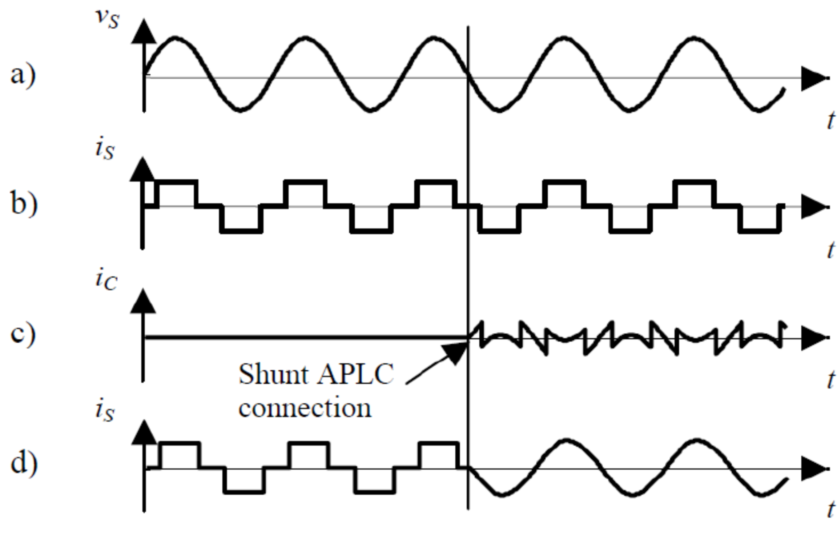


Figure 3.1.(ii)Performance scheme of a shunt APLC

The current waveform of a nonlinear load, a three-phase diode rectifier with a highly inductive DC branch, is shown in Figure 3.1(ii)b. Alter the shunt APLC connection, this injects a compensation current, Figure 3.1(ii)c, in parallel with the load. Figure 3.1(ii)d shows the source current of the system. Before the compensation is equal to the current load, and after it is sinusoidal. In this example, the source voltage is sinusoidal, Figure 3.1(ii)a.

3.2.2 Series Active Filters

Figure 3.2.(a)shows the connection scheme of a series APLC. It is connected to the system through a coupling transformer. The compensation voltage, v_C, is used to cancel the voltage harmonics of the load, *e.g.* diode rectifiers with high capacitance in the DC side.

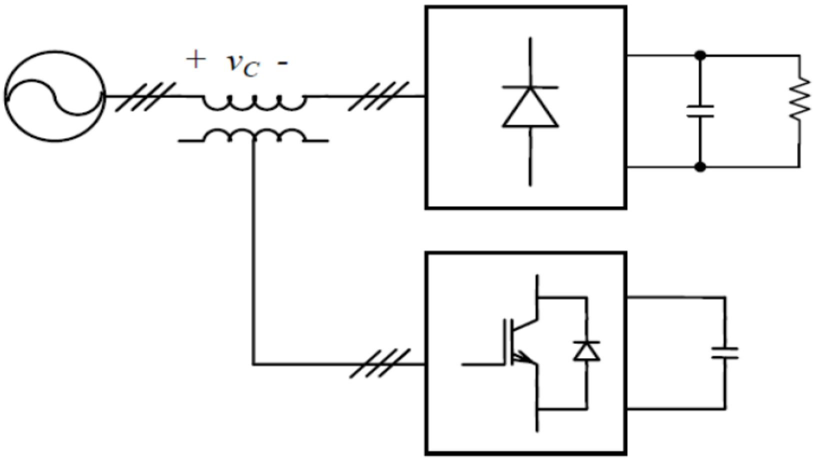


Figure 3.2.(i)A series APLC scheme

The performance scheme of a series APLC is shown in Figure 3.2.(ii). Different control targets are possible. In this case, the APLC supplies a compensation voltage, Figure 3.2.(ii)b, when it is connected. These harmonic components cancel the voltage harmonics of the load, Figure 3.2.(ii)a. So, after the compensation, the source voltage will be sinusoidal, Figure 3.2.(ii)c.

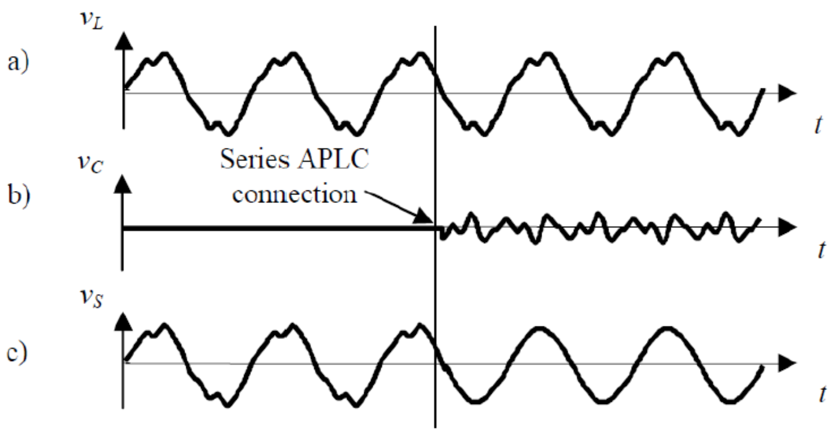


Figure 3.2.(b) Performance scheme of a series APLC

3.2.3 Hybrid Filters

The next figures show some hybrid passive and active filters. The basic aim of these combinations is to reduce the cost of the static compensation. The passive filters are used to cancel the most relevant harmonics of the load, and the active filter is dedicated to improving the performance of passive filters or to cancel other harmonics components. As result, the power of the active filter is reduced, and the passive filter problems (*e.g.* resonances with the source impedance) are mitigated.

In summary, the total cost decreases without reduction of the efficiency. Figures 3.3(a), 3.3(b) and 3.3(c) show the more usual hybrid topologies.

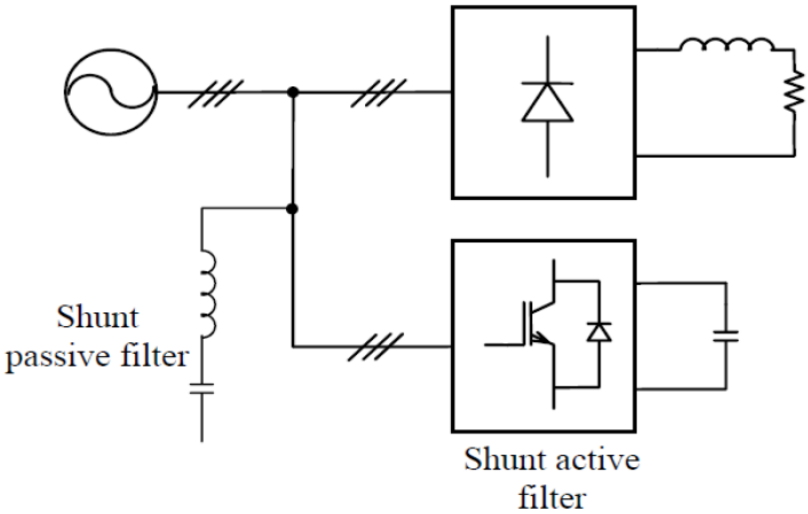


Figure 3.3(a). Hybrid filter with a shunt passive filter and a shunt active filter

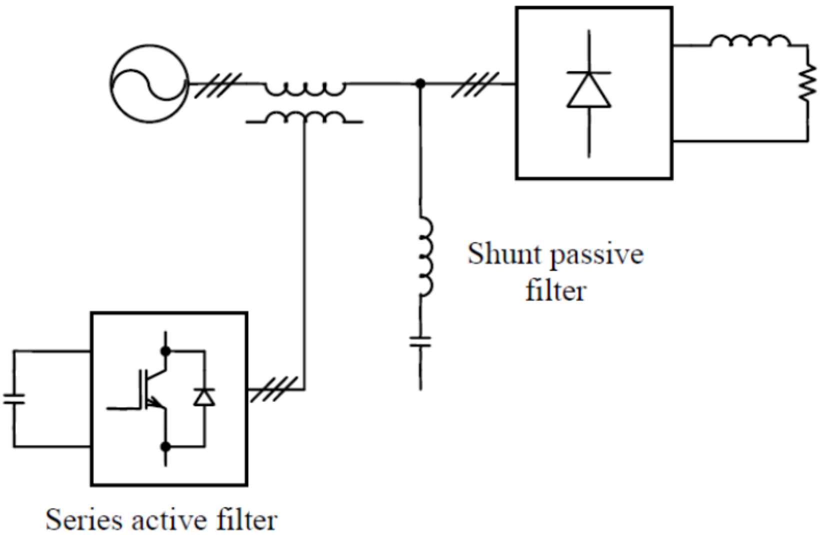


Figure 3.3(b). Hybrid filter with a shunt passive filter and a series active filter

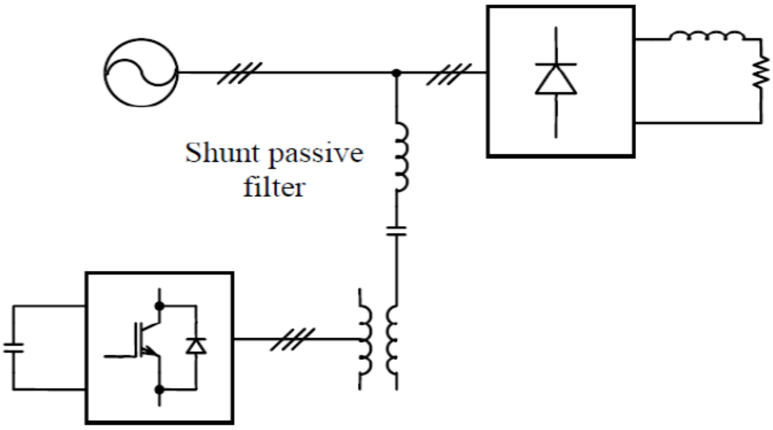


Figure 3.3(c).A shunt passive filter and an active filter in series with it

The passive filter is designed with some LC branches resonant to some harmonics or adjusted as high-pass filter. The main characteristics of the presented hybrid topologies are summarized in Table 3.1.

Table 3.1. Comparison between the different hybrid topologies

	Shunt active filter + shunt passive filter	Series active filter + shunt active filter	Active filter in series with a shunt passive filter
Power circuit of active filter	PWM inverter with closed-loop current control	PWM inverter without current control	PWM inverter with or without closed-loop current control
Main aim of active filter	Current-harmonic compensation	Harmonic insolate and voltage-harmonic compensation	Harmonic compensation or to improve the passive filter
Advantages	Reactive power regulation Commercial active filters	There is no harmonic current in active filter Commercial passive filters	Low protection of active filter Commercial passive filters
Disadvantages	Compensation intervals	Over-currents. There is no reactive power control	There is no reactive power control

Chapter-4

APLC POWER STAGE

Power-electronic Inverters in APLCs

Voltage-source Inverter Topologies

Control of Voltage-source Inverters

Power-electronic Inverters in APLCs

There are two kinds of power circuits in an APLC :

- Voltage source inverter (VSI). It is a DC/AC inverter with a capacitor in the DC side. It works as a voltage source.
- Current source inverter (CSI). It is an inverter with an inductance in DC side. It works as a current source.

The corresponding three-phase power circuits are shown in Figures 4.1(a) and 4.1(b) respectively.

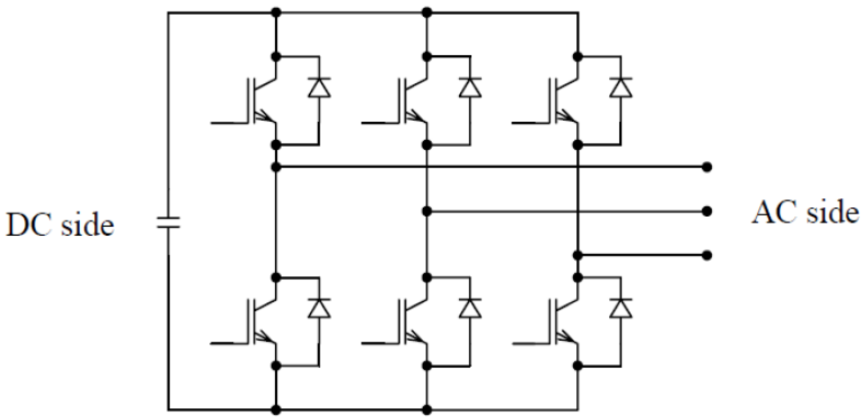


Figure 4.1(a). Power circuit of a VSI inverter

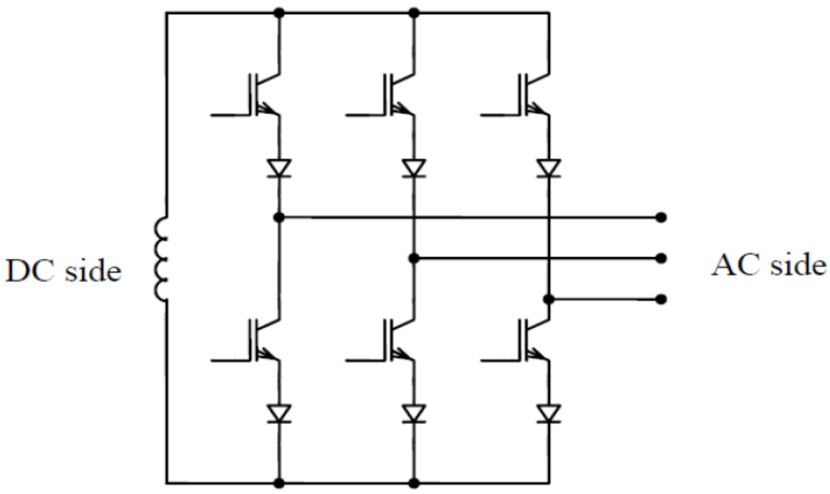


Figure 4.1(b). Power circuit of a CSI inverter

The usual converter switching devices are insulated gate bipolar transistors (IGBTs). In the DC side, a capacitor (in the VSI configuration) or an inductance (in the VSI configuration) is the energy stored. The inverter does not need an additional energy source in the DC side. So, the APLC control will enable the electrical system to provide the converter energy losses. The VSI topology cost is lower and it is the usual extended configuration. Table 4.1 compares the main power-device characteristics. These values were presented by Akagi.

Table 4.1. Power-device characteristics.

Switching devices	Power of active filter	Voltage and current limits	Power-circuit topology	Switching frequency	Year
GTO	20 MVA	4500 V 3000 A	VSI	300 Hz	90
SI	200 MVA	1200 V 300 A	VSI	5 kHz	88
BJT	500 MVA	1200 V 300 A	VSI	1.3 kHz	87
IGBT	100 MVA	1000 V 100 A	VSI	8 kHz	88

Nowadays, the performance limits have been augmented, but the comparison shows than the IGBT works with a switching frequency over the rest (about 25 kHz in actuality). Besides, its energy losses are low. For this, the IGBT is the more usual switching device. The GTOs are used in some applications where it is necessary to work with a very high voltage or current.

4.1 Voltage-source Inverter Topologies

As was mentioned above, an active filter uses a DC/AC inverter as a power circuit. A DC voltage value is connected to the load in an alternative way to synthesis a desired waveform in the AC side.

The shunt APLC use a VSI inverter, because it is possible to obtain a high efficiency with a low initial cost. In the next section, the basic performances of the VSI converter are described. Single-phase and three-phase configurations are presented.

4.1.1 Single-phase Full-bridge Inverters

Figure 4.2 shows two possible schemes of a single-phase inverter. In this analysis, ideal switching devices and a constant-voltage source in the DC side have been considered. Figures 4.2 a, b present a half-bridge and a full-bridge configuration, respectively.

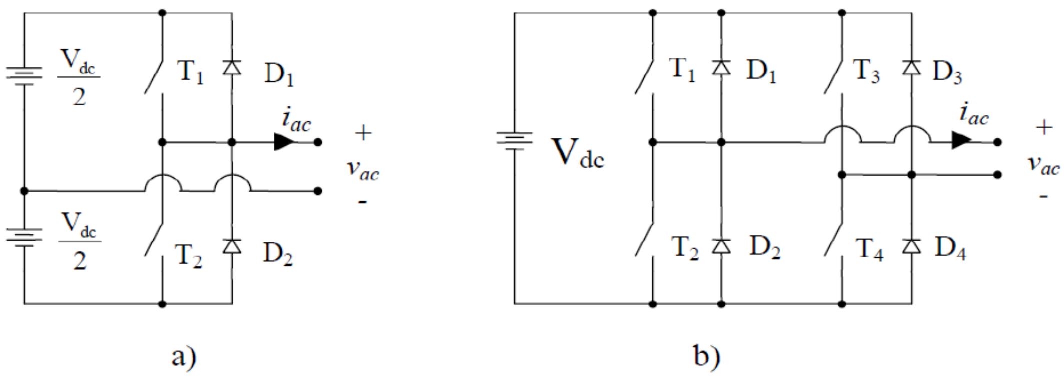


Figure 4.2. Basic schemes of an ideal inverter

The adequate ON/OFF connection of ideal switches allows a rectangular waveform in the AC side. In an half-bridge scheme, if T_1 is ON and T_2 is OFF, the output voltage will be $+V_{dc}/2$. If T_1 is OFF and T_2 is ON, the output voltage will be $-V_{dc}/2$. In the full-bridge scheme, if T_1 and T_4 are ON and T_2 and T_3 are OFF, the output voltage is V_{dc}. When T_2 and T_3 are OFF and T_1 and T_4 are ON, the output voltage is $-V_{dc}$. When an inductive load is connected in the AC side, it is necessary to include shunt diodes with each switch. The inductive current is delayed with regard to the voltage. If the switches change the position, *e.g.* T_1 and T_4 in Figure 4.2b, the current needs a freewheeling way through diodes D_2 and D_3. The current can flow in the same way in the AC side. In this period, the load returns the energy to the DC source. For this reason, the diodes are called energy-recover or freewheeling diodes. If the load is resistive, the diodes will not be necessary.

In Figure 4.2(c), a sinusoidal current has been built with a half-bridge inverter. It is a basic commutation scheme of a rectangular waveform. The desired waveform is the fundamental component, also included in Figure 4.2(c).

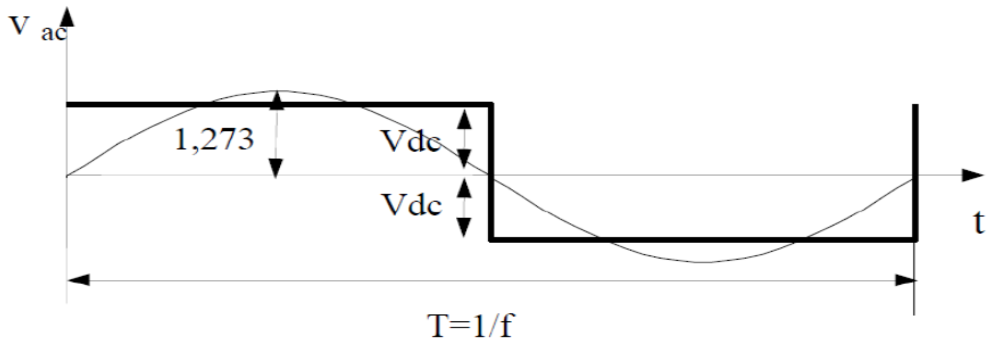


Figure 4.2(c). Sinusoidal waveform from a single-phase inverter, with a quadrangular switching pulse

In effect, the Fourier decomposition allows the first harmonics of a rectangular waveform to be obtained:

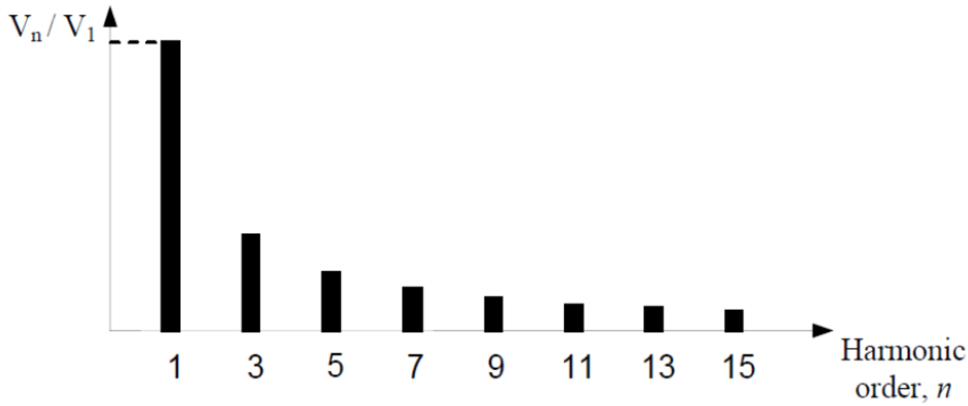


Figure 4.2(d). Harmonic spectrum of Figure 9.12 waveform

The output signal frequency can be modified by the switch commutations. The amplitude can be adjusted by the DC voltage value or by the switch pulse modulation. This is the more practical and usual procedure. There are two possibilities. The first one is modulating constant-width pulses and the second one is a sinusoidal modulation in a period.

The output voltage is an alternated waveform. It includes the desired sinusoidal output voltage and other non-desired frequencies as a result of device commutations. The current waveform depends on the output load. If the load is resistive, the current waveform is the same as the voltage waveform. If the load is inductive, the current waveform is smoother than the voltage waveform, and their non-desired harmonic components will be reduced. For this reason, an output inductance will be fixed in the AC side. This inductance is not enough to filter all no desired frequencies of output voltage, and it is convenient, in a general case, to add a LC passive filter.

The usual electronic switches are BJTs, MOSFETs or IGBTs. Figure 4.3shows the previous inverter schemes designed by IGBTs, the more extended device.

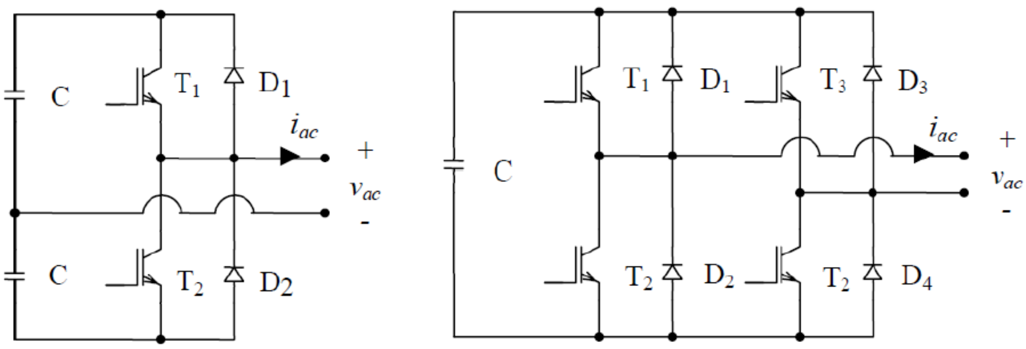


Figure 4.3.VSI single-phase inverter schemes with IGBTs, (a) a half-bridge, (b) full bridge

An IGBT is a hybrid combination of a BJT and a FET power device. Its performance is similar to a BJT, but the gate current is very low, as in a FET. The commercial power transistors include the freewheeling diodes. The dc voltage is fixed by one or two capacitors, according to the configuration.

4.1.2 Three-phase Full-bridge Inverters

A three-phase inverter can be built with three single-phase inverters connected to the same DC source. Also it is possible to design a three-phase configuration as is presented in Figure 4.4(a).

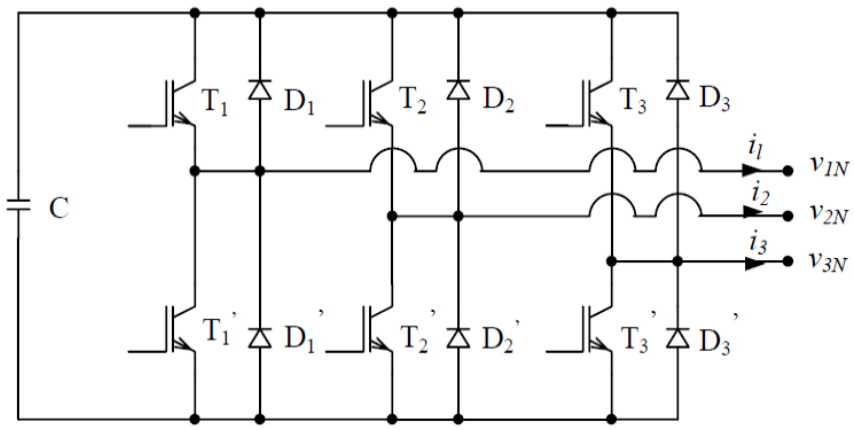


Figure 4.4(a).VSI three-phase full-bridge inverter with IGBTs

Figure 4.4(b) shows the three-phase inverter performance in generating sinusoidal three-phase voltages, V_{1N}, V_{2N}, V_{3N}. It is considered as only a switching pulse along the conduction period. In this configuration, it is necessary to apply complementary pulses in the top and bottom IGBT of each branch. There are some periods where T_1-T_2-T_3 are ON and periods where T_1'-T_2'-T_3' are ON. The three output line-to-neutral voltages and a line-to-line voltage, with their fundamental component are presented.

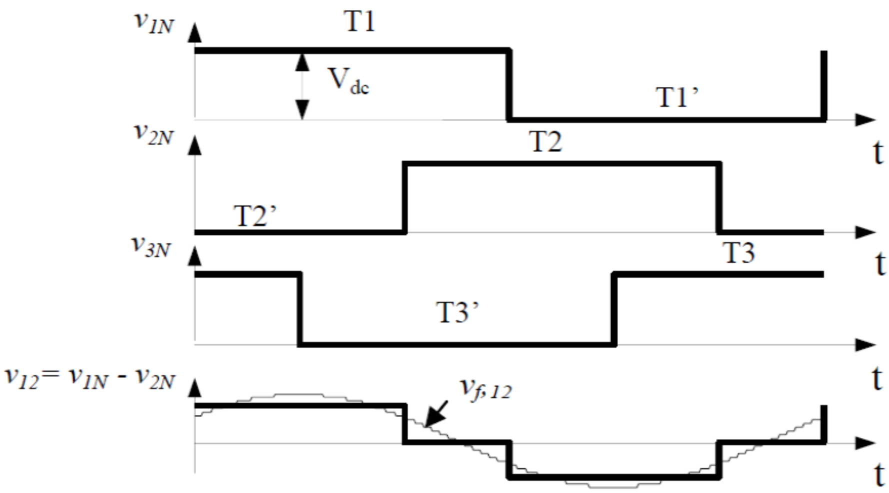


Figure 4.4(b). Output voltages in a three-phase inverter with square-wave switching

Figure 4.4(c) shows the voltage-harmonic spectrum, where the harmonic amplitude values are relative to the fundamental component. The use of poly phase systems allows a reduction in the presence of harmonics. The PWM techniques will reduce the harmonic distortion significantly.

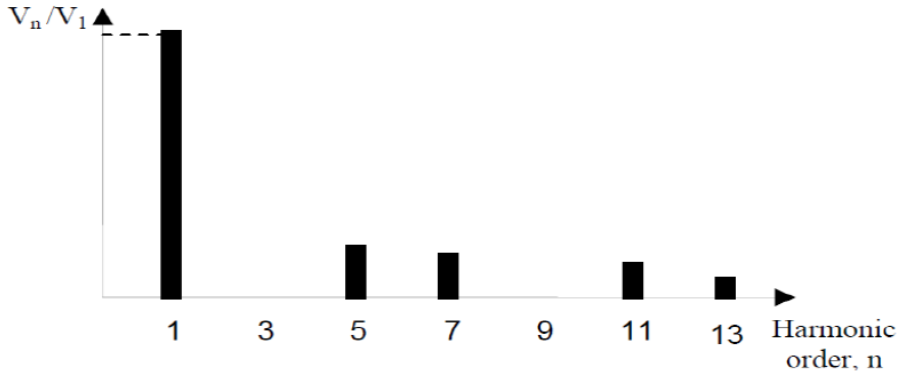


Figure 4.4(c).Harmonic spectrum of line-to-line voltage *v12*

It is possible to use different power circuits in shunt three-phase APLCs. Inlow-power applications, it is usually a three-phase scheme. Figure 4.5(a)shows a three-phase three-wire system compensated by a shunt APLC. The power circuit has three IGBTs branches with a capacitor in the DC side.

In this simple scheme, the connection between the APLC and the system is realized by means of an output inductance. When the APLC output voltages are positives, the output currents increase. When the voltages are negatives, the currents decrease. The quadrangular output voltages will produce triangular output currents. A correct design of output inductances (and *a posteriori* passive filter) is very important to get an adequate active conditioner answer. The increment of compensation current will allow, or not, to follow the reference of control.

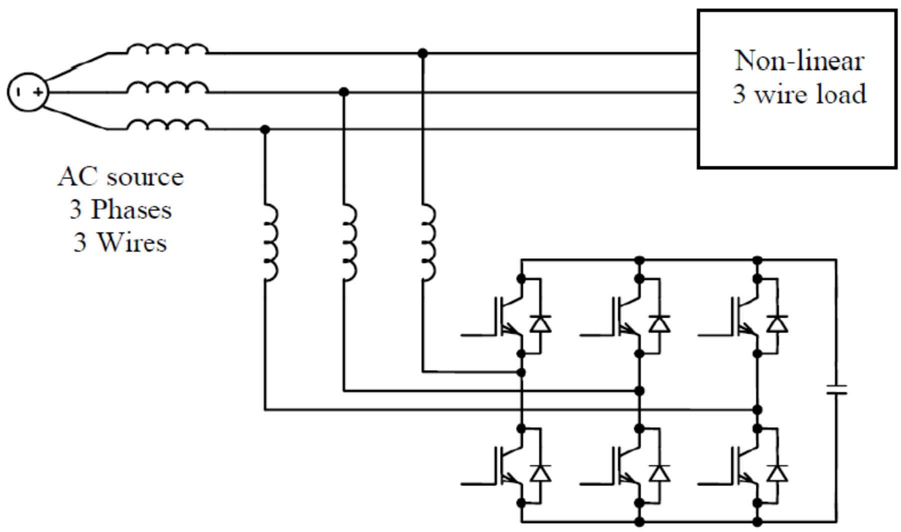


Figure 4.5(a). Three-phase three-wire system scheme, with a nonlinear load compensated by a shunt APLC using a VSI three-phase inverter

In three-phase four-wire systems with unbalanced loads, it is possible to use three single-phase inverters as an APLC power circuit. The aim is to compensate phase by phase. Figure 4.5(b) shows a three-phase four-wire system with a nonlinear load compensated by a shunt APLC. The network connection needs a coupling transformer, because there is no a common neutral point.

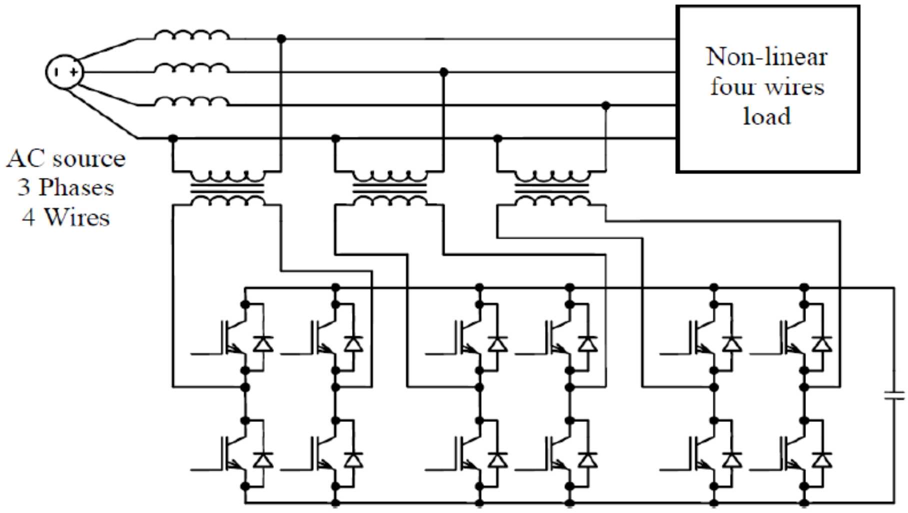


Figure 4.5(b). Three-phase, four-wire system scheme, with a nonlinear load compensated by a shunt APLC using three single-phases as an APLC power circuit

In general, in four-wire power systems, it is usual to use APLCs with three phase configurations. In this case, a split capacitor is necessary in the DC side. The middle point is connected to the neutral wire.

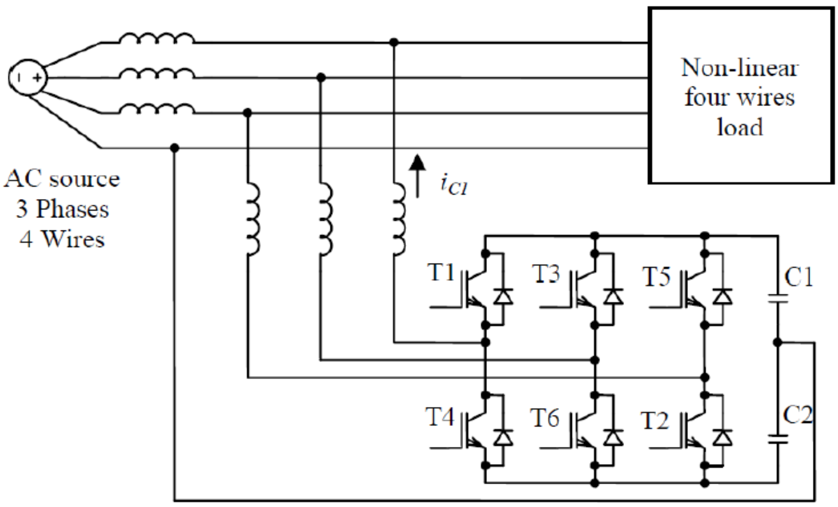


Figure 4.5(c). Three-phase, four-wire system scheme, with a nonlinear load compensated by a shunt APLC using a three-phase three-leg APLC power circuit

This scheme has a problem when the compensation currents have sequence zero components. In this case, these current will flow through one only DC capacitor. As a result, the DC capacitor voltage will be unbalanced. This implies a malfunction in the inverter performance, and some solutions have been proposed. Figure 4.6 summarises, *e.g.*, all the situations when the APLC follows a sinusoidal reference.

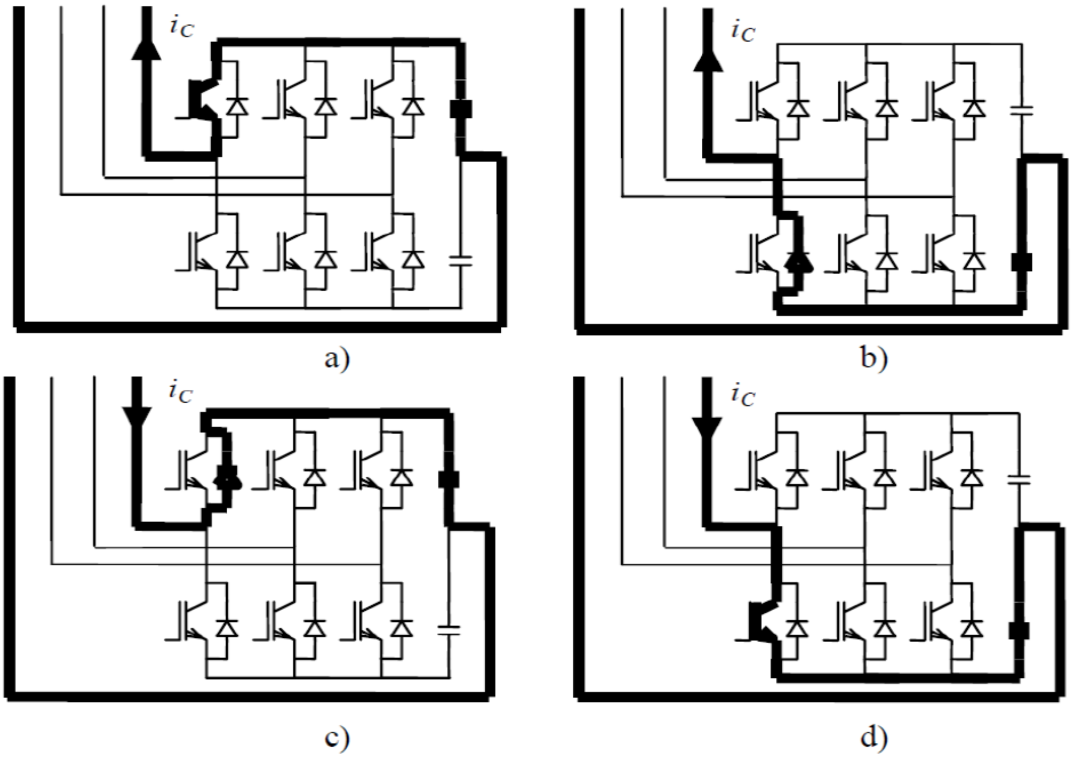


Figure 4.6. Neutral compensation current in a three-phase inverter with a DC split capacitor

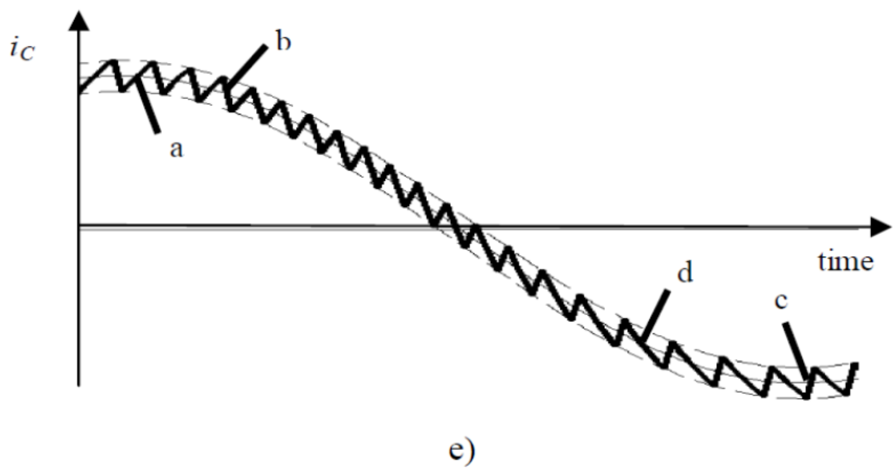


Figure 4.6. Neutral compensation current in a three-phase inverter with a DC split capacitor (contd.)

In this example, the inverter uses a hysteresis band PWM control to follow the sinusoidal reference. If the compensation current i_C is increasing and positive ($i_C > 0$, $di_C/d > 0$), the current will flow through T_1 and C_1, and the C_1 voltage will decrease. Figure 4.6shows other possible situations. Table 4.2 summarises all the voltage variations.

Table 4.2. Voltage variations of DC capacitors in a three-branch, four-wire inverter

cases	i_C	di_C/dt	Voltage variations
a	$i_C > 0$	$\frac{di_C}{dt} > 0$	C1 voltage decreases
b	$i_C > 0$	$\frac{di_C}{dt} < 0$	C2 voltage increases
c	$i_C < 0$	$\frac{di_C}{dt} > 0$	C1 voltage increases
d	$i_C < 0$	$\frac{di_C}{dt} < 0$	C2 voltage decreases

When the compensation current does not present a zero-sequence component, the voltage unbalance is not important. Anyway, it is possible to implement a proportional or proportional-integral control block to adjust the signal reference using the capacitor voltage difference. This allows balancing of their voltages.

Other inverter configurations are possible to avoid the problem mentioned above. Figure 4.5(b) shows a three-phase inverter with four IGBT branches.

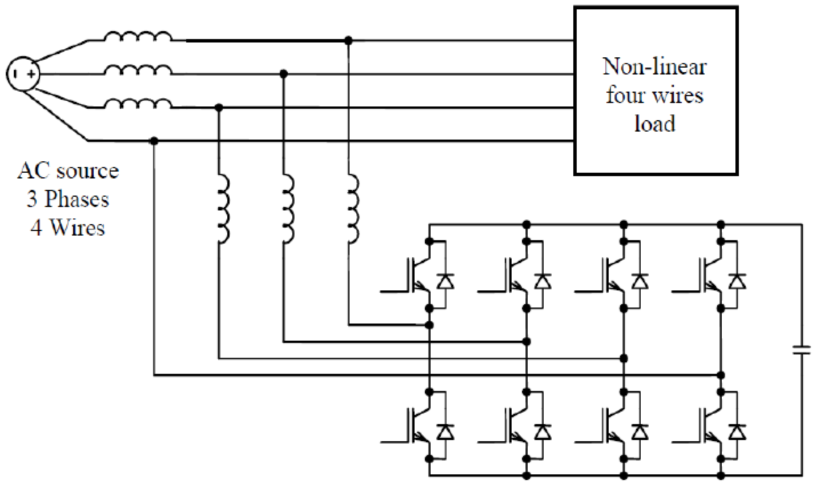


Figure 4.5(d). Three-phase four-wire system with a nonlinear load compensated by a shunt APLC, using a three-phase, four-arm APLC power circuit

In this case, the middle point of the fourth arm is connected to the neutral wire. The control of these IGBTs allows fixing of the neutral voltage and it avoids voltage unbalance. Anyway, this scheme is not extended because it uses more devices.

4.2 Control of Voltage-source Inverters

The main advantages of modern power-electronic converters are being achieved through the use of the so-called switch-mode operation, in which power semiconductor devices are controlled in an on/off fashion, with no operations in the active region.

4.2.1 Techniques of Closed-loop PWM Current Control

In this section, the main closed-loop current techniques used in shunt APLC control will be presented. In the APLC control block, the inputs are the load voltage and current signals, and the outputs are the compensation current references, depending on the control strategy. The APLC power circuit will inject the compensation currents using a closed-loop PWM current control.

For this, APLC output currents are measured and compared with their references. A current controller uses the error signals to generate the IGBT trigger signals. These pulses allow to be changed the electronic switch states. The goal is to reduce the current errors.

The main closed-loop current controls through the pulse-width modulation are:

- Periodical sampling, PS;
- Hysteresis band, HB;
- Triangular carrier, TC.

In the periodical sampling method, the switching devices change with a periodical switch bipolar wave. At these times, the output signal is compared with their reference. If it is bigger, the switches change and the output voltage becomes negative. So, the real signal will decrease. On the other hand, if it is less, the switches change to obtain a positive output voltage. Then, the real signal will increase. A general control scheme is presented in Figure 4.7(a). In this case, the reference signal is sinusoidal. Figure 4.7(a) shows that the error signals allow to be obtained the trigger pulses to control all the IGBT gates.

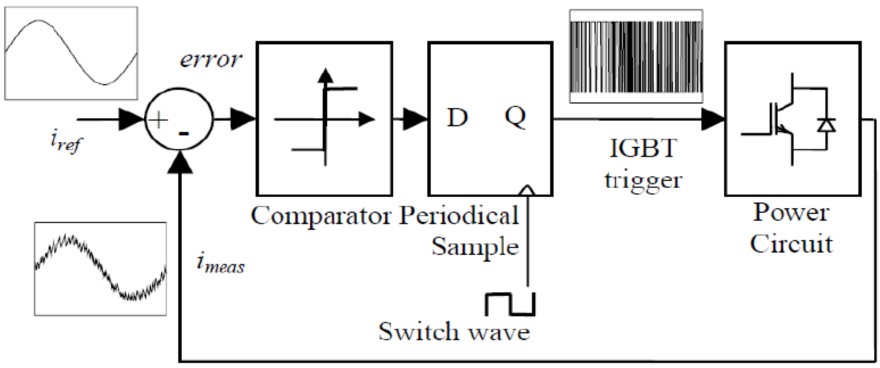


Figure 4.7(a). Control scheme of periodical sampling

Figure 4.7(b) presents a period of different waveforms: the reference current, the output current and the trigger signal. If the power circuit is a single-phase half bridge inverter, these trigger signals will be the upper IGBT gate pulses. The complementary signal will be the bottom IGBT gate pulses. It is easy to implement this control method, but the average error is not null.

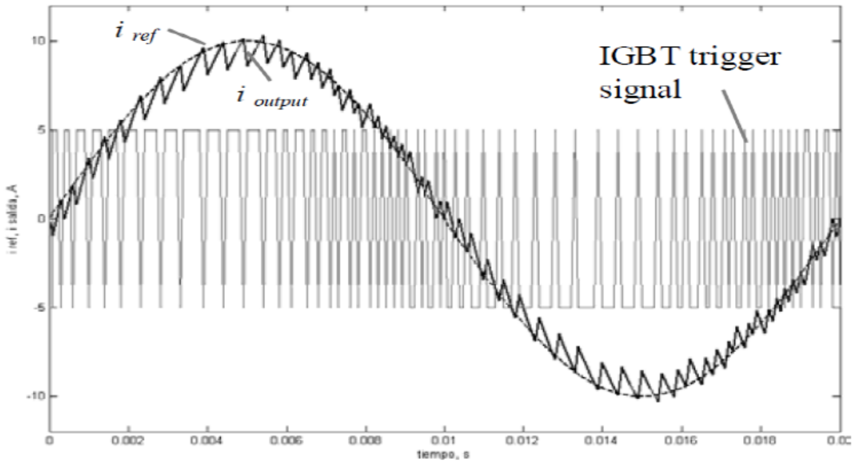


Figure 4.7(b). Waveforms in a periodical sampling control method

The hysteresis band control is presented in Figure 4.8(a). A single-phase inverter and a sinusoidal reference are considered. When the measured current crosses a band around the reference current, the switch devices change (it turns ON or OFF) and the current returns to the band.

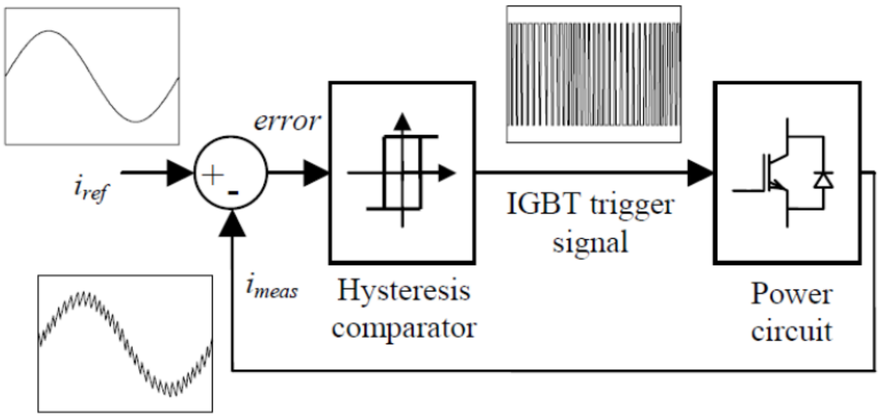


Figure 4.8(a). Control scheme of hysteresis-band method

The control performance is next: the currents are measured and compared with the reference ones; the error signals are the inputs of a hysteresis comparator; their outputs are the IGBT trigger pulses. If the measured current is bigger (a half of the band value) than the reference one, it is necessary to commute the corresponding switch devices to get a negative inverter output voltage; this voltage allows to be decreased the output current, and it goes to the reference current. On the other hand, if the measured current is less (a half of the band value) than the reference one, the switch devices commute to obtain a positive inverter output voltage; the output current increases, and it goes to the reference current. As a result, the output current will be in a band around the reference current.

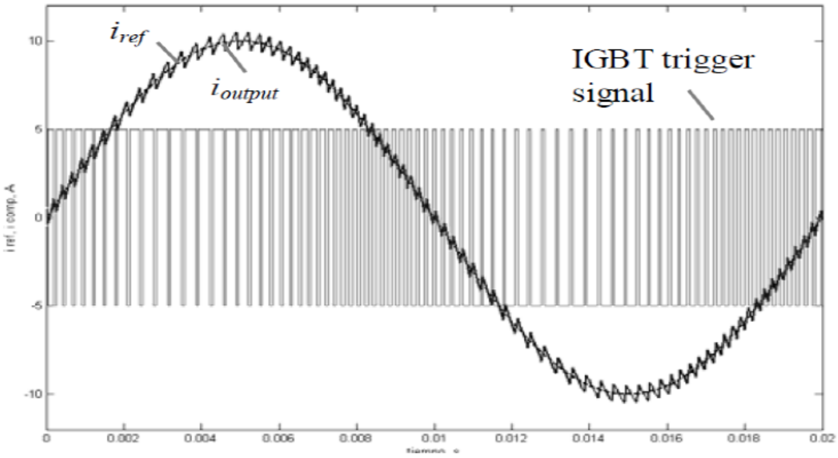


Figure 4.8(b). The main waveforms in a hysteresis-band control method

The implementation of the hysteresis-band control is not expensive and the dynamical answer is excellent. It allows a fast current control. Therefore, in this control it is not possible to fix the commutation frequency. This disadvantage is not ever critical, and this method is one of the more extended closed-loop current controls.

In the triangular-carrier method, the pulse sequences of the PWM control are calculated by comparing the current error signal with a triangular carrier, as Figure 4.9(a) shows. It is usual to include, *e.g.*, a proportional integral gain (PI control) to process the error signal. The *kp* and *ki* parameters determine the stationary error and the dynamical answer of the control.

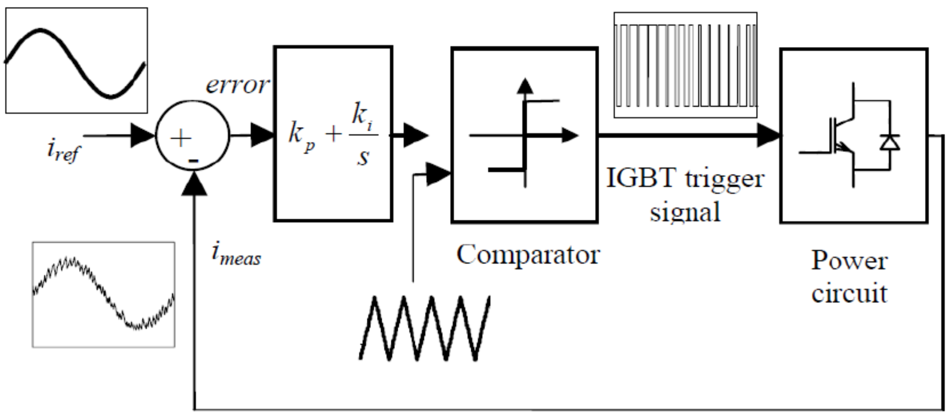


Figure 4.9(a). Triangular carrier PWM control of a single-phase inverter

This method uses a triangular wave of a fixed frequency. So, the converter device commutation frequency is constant. In contrast to this advantage, there are some disadvantages. There are amplitude and phase errors in the output current, and there are some intervals where the converter state corresponds to a null output voltage.

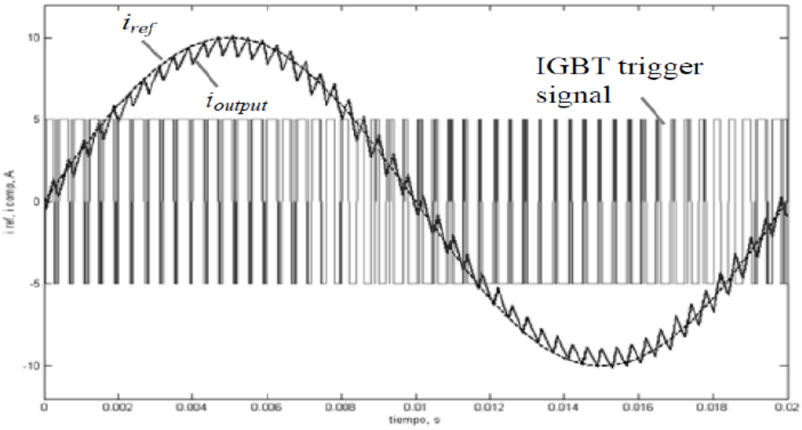


Figure 4.9(b). The main waveforms in the triangular-carrier current-control method

In any modulation method, the APLC output current will include no desired high frequencies, because the switch device's commutation frequency is not high enough. So, it is necessary to design an APLC output passive filter to eliminate these high-frequency components.

Chapter-5

STRATEGIES OF LOAD COMPENSATION

Self Tuning Filter

Harmonic Isolator

Proposed APLC Block

Strategies for Load Static Compensation

The election of strategy control is essential to get the desired compensation aim. Many strategies in the time domain and in the frequency domain have been proposed. Some of these are modifications of the Akagi *p–q* theory, [1]. This theory is based on a coordinates transformation, from *a–b–c* (or 1–2–3) axes to new α–β–0 axes. In these coordinates, the compensation current references are calculated, as Section 5.2 will describe.

5.1 Self tuning filter

The self-tuning filter (STF) was first used in order to estimate the phase angle of PWM converter outputs. The transfer function is obtained from the integration of the synchronous reference [9]. The transfer function is defined as

$$H(S) = \frac{V_{xy}(S)}{U_{xy}(S)} = \frac{S + j\omega}{S^2 + \omega^2} \tag{6}$$

where,

$$V_{xy}(t) = e^{j\omega t} \int e^{-j\omega t} U_{xy}(t) dt \tag{7}$$

The STF has a magnitude and phase response that is similar to those of a general band-pass filter. Apart from the integral effect on the input magnitude, the STF does not alter the phase of the input, i.e. the input Uxy(s) and output Vxy(s) have the same phase. Note that in order to have unit magnitude, i.e. |H(s)| = 0 dB, a constant k is incorporated in to (26), that is,

$$H(S) = \frac{V_{xy}(S)}{U_{xy}(S)} = k\frac{(S+k) + j\omega}{(S+k)^2 + \omega^2} \tag{8}$$

In the stationary reference, the fundamental components are given by:

$$\overline{V}_{\alpha}(S) = \frac{k}{S}\left[V_{\alpha}(S) - \overline{V}_{\alpha}(S)\right] - \frac{\omega}{S}\overline{V}_{\beta}(S) \tag{9}$$

$$\overline{V}_{\beta}(S) = \frac{k}{S}\left[V_{\beta}(S) - \overline{V}_{\beta}(S)\right] - \frac{\omega}{S}\overline{V}_{\alpha}(S) \tag{10}$$

The STF can be used as a simple but effective method of suppressing the effects of a non-ideal source, which allows for improved harmonic compensation by the APF.

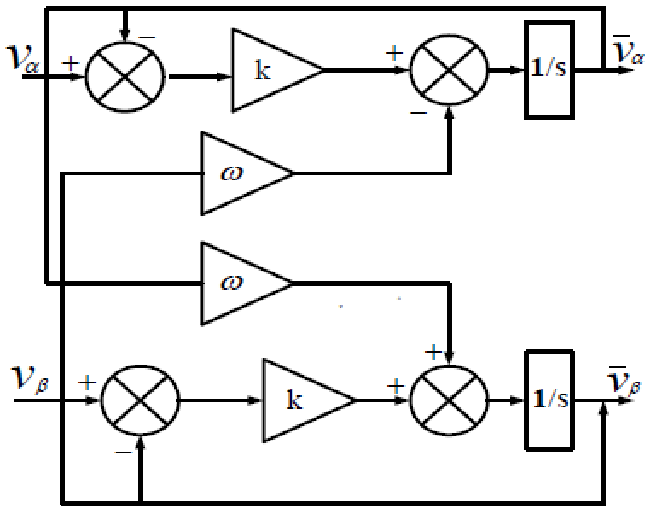


Fig. 5.1 STF tuned to the pulsation w_c

5.2 Harmonic isolator

The load currents, i_{La},i_{Lb} and i_{Lc} of the three-phase threewiresystem are transformed into the α-β axis (Fig. 5.2) as

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \tag{11}$$

As is known, the currents in the α-β axis can be respectively decomposed into DC and AC components by

$$i_\alpha = \hat{i}_\alpha + \tilde{i}_\alpha \,,$$
$$i_\beta = \hat{i}_\beta + \tilde{i}_\beta . \tag{12}$$

Then, the STF extracts the fundamental components at the pulsation w_c directly from the currents in the α-β axis. Afterwards, the α-β harmonic components of the load currents are computed by subtracting the STF input signals from the corresponding outputs (Fig. 5.2.). The resulting signals are the AC components, $\tilde{i}_\alpha$ and $\tilde{i}_\beta$, which correspond to the harmonic components of the load currents i_{La},i_{Lb} and i_{Lc} in the stationary reference frame.

For the source voltage, the three voltages v_{Sa}, v_{Sb} and v_{Sc} are transformed to the α-β reference frame as

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{Sa} \\ v_{Sb} \\ v_{Sc} \end{bmatrix} \tag{13}$$

Then, self-tuning filtering is applied to these α-β voltage components. This filter allows suppressing of any harmonic component of the distorted mains voltages and consequently leads to improvement of the harmonic isolator performance.

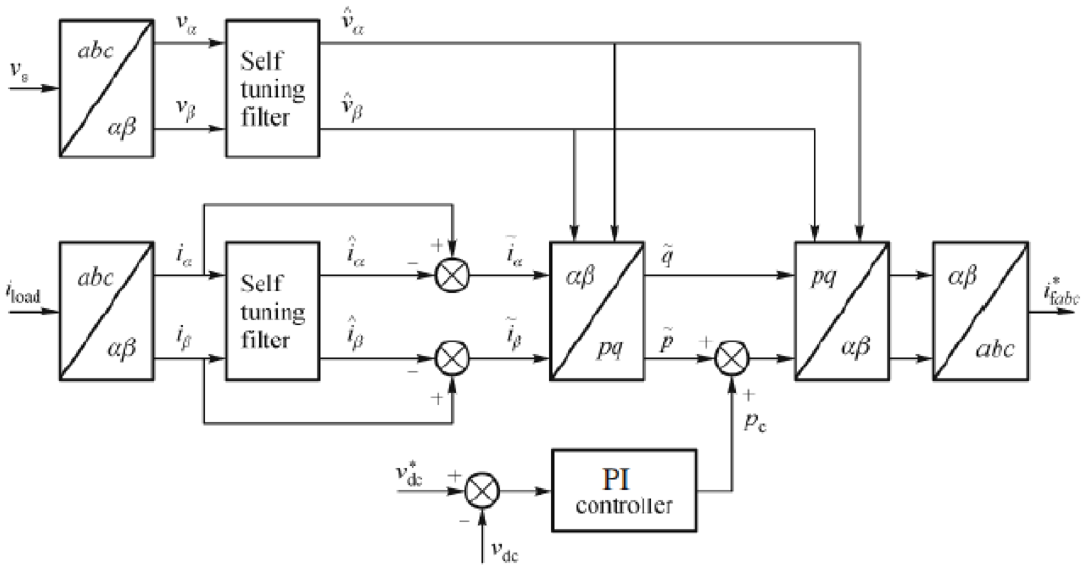


Figure 5.2 Block diagram of STF based harmonic isolator

After computation of the fundamental component $\hat{v}_{\alpha\beta}$ and harmonic currents $\hat{\imath}_{\alpha\beta}$, the p and q powers are given as

$$p = i_\alpha \hat{v}_\alpha + i_\beta \hat{v}_\beta, \text{ (Instantaneous active power)} \tag{14}$$

$$q = i_\beta \hat{v}_\alpha - i_\alpha \hat{v}_\beta, \text{ (Instantaneous reactive power)} \tag{15}$$

where, $p = \hat{p} + \tilde{p}$,

$q = \hat{q} + \tilde{q}$.

in which $\hat{p}$ and $\hat{q}$ are fundamental components and$\tilde{p}$ and $\tilde{q}$are alternative components.

The power components $\tilde{p}$ and $\tilde{q}$related to the same α-βvoltages and currents can be written as

$$\begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix} = \begin{bmatrix} \hat{v}_\alpha & \hat{v}_\beta \\ -\hat{v}_\beta & \hat{v}_\alpha \end{bmatrix} \begin{bmatrix} \vec{\imath}_\alpha \\ \vec{\imath}_\beta \end{bmatrix} \tag{16}$$

After adding the active power required for regulating DC bus voltage, pc, to the alternative component of the instantaneous real power $\tilde{p}$ (Fig. 4), the current references in the α-β reference frame, $i_{\alpha\beta}$, are calculated by

$$i_\alpha^* = \frac{\hat{v}_\alpha}{\hat{v}_\alpha^2+\hat{v}_\beta^2}(\tilde{p}+p_c) - \frac{\hat{v}_\alpha}{\hat{v}_\alpha^2+\hat{v}_\beta^2}\tilde{q} \ , \tag{17}$$

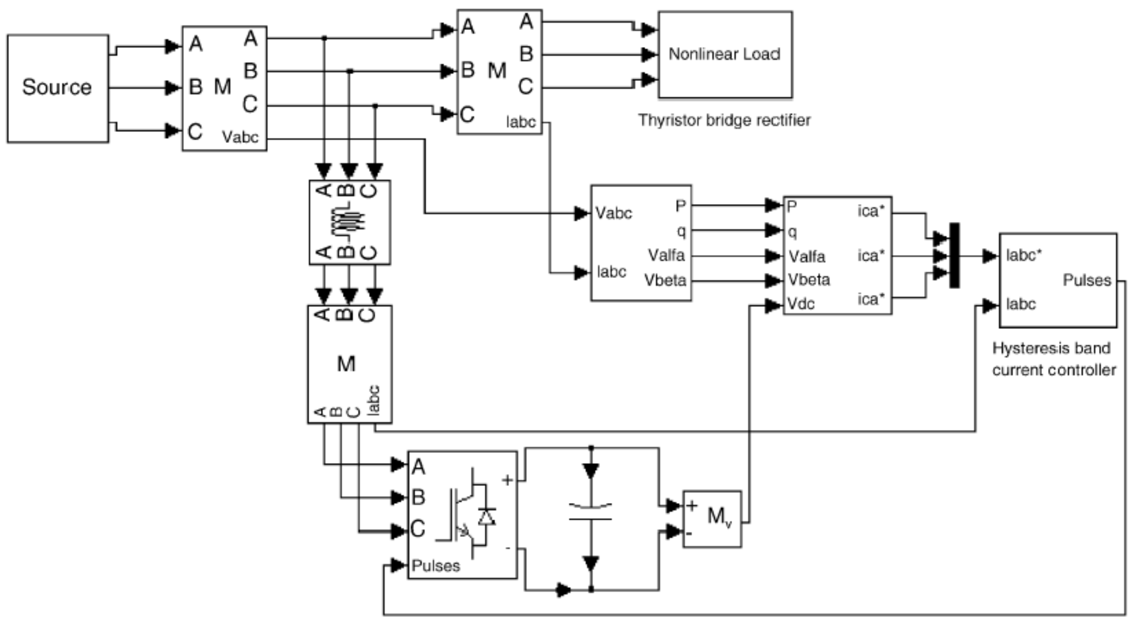
$$i_\beta^* = \frac{\hat{v}_\beta}{\hat{v}_\alpha^2+\hat{v}_\beta^2}(\tilde{p}+p_c) - \frac{\hat{v}_\alpha}{\hat{v}_\alpha^2+\hat{v}_\beta^2}\tilde{q} \ . \tag{18}$$

Then, the filter reference currents in the a-b-c coordinates are defined by

$$\begin{bmatrix} i_{fa}^* \\ i_{fb}^* \\ i_{fc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix}. \tag{19}$$

5.3 Proposed Method

The proposed shunt APLC block diagram and the main section of the active power line conditioners shown in figure is force- commutated voltage source inverter connected to a dc capacitor. Current harmonics is achieved by injecting equal but opposite current harmonics components at the PCC (point of common coupling), there by canceling the original distortion and improving the power quality on the connected power system.



5.3 Schematic block diagram of three-phase shunt APF system.

Chapter-6

Practical Design

Component-design Considerations

Simulation Analysis

Conclusion

Practical Design

The control block calculates the compensation current references according to the APLC control strategy. The power circuit follows these references using a PWM method. The switching frequency of converter electronic devices has to be high to follow any reference. The limits are fixed by the actual technology. These commutations force no desired frequencies into the compensation currents, and consequently into the source current. So, it is necessary to include an inductance and/or a LC passive filter in the output converter to eliminate (or to mitigate) these no desired high frequencies. The parameters of these passive elements will condition the APLC performance.

The APLC design performance can be simulated via a software platform.This process will allow the different model values to be contrasted and the stationary and dynamical APLC performance to be adjusted. This optimises the final implementation. In this case, the simulation probes have been developed in MATLAB® and Simulink® software. The Power System Blockset includes electrical elements to configure the source, the load and the filter used in the active compensation.

6.1 Component-design Considerations

As was mentioned above, with any modulation method, the compensation current includes no desired high-frequency harmonic components. A passive filter in the APLC output in used to filter these components [10].

The APLC power circuit presents a quadrangular voltage in the output. These positive and negative voltages imply an increasing or decreasing output current when the load is inductive. It allows the reference current calculated by the control block to b followed. The output current noise depends on commutation frequency. Today, the IGBT commutation frequency is around 20–25 kHz.

On the one hand, an output inductance L reduces some high-frequency components of the output current. The value of L and the voltage value of the converter DC side capacitors fix the gradient of the compensation current. So, they determine the active conditioner dynamical answer. The scheme of Figure 6.1(a) shows the APLC network connection with an output inductance L. The DC output voltage of the APLC power circuit is V_{DC} when the IGBTs voltage drop is not considered. A sinusoidal network waveform has $\sqrt{2}\ V_{NET}$ volts as its amplitude.

In Figure 6.1(a), i_S, i_L and i_C are the source, the load and the compensation current, respectively. The compensation current gradient is:

$$\frac{d\,i_C}{dt} = \frac{1}{L}\left(V_{DC} - \sqrt{2}\,V_{NET}\right).$$

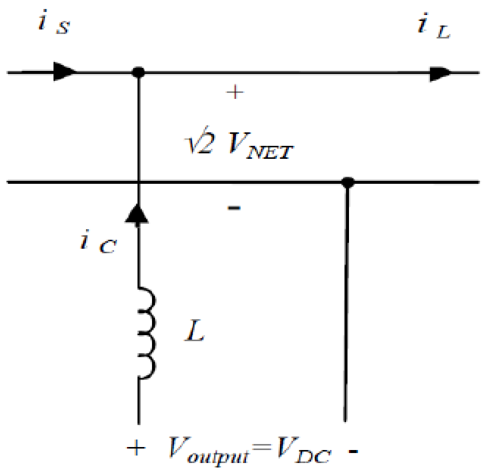


Figure 6.1(a). APLC network connection through an output inductance

The compensation current gradient increases when the converter DC voltage is high or the output inductance low. In this case, the dynamical answer is fast but the output current ripple is high. If the converter DC voltage is low or the inductance is high, the APLC answer will be poor but the current ripple will be minor. So, an equilibrated election of L and V_{DC} values is necessary.

Two main design considerations are the following:

- To limit the harmonic amplitude corresponding to the commutation frequency.
- To get a compensation current gradient higher than the load current gradient.

The usual DC voltage and inductance values to limit the harmonic amplitude of commutation frequency satisfy:

$$\frac{I_{fc}}{I_1} = \frac{V_{fc}}{I_1 L 2\pi fc} < 5\% ,$$

$$V_{DC} > \left(L\frac{di_L}{dt} + \sqrt{2}V_{RED} \right),$$

where *fc* is the commutation frequency, and *Vfc* and *Ifc* are the rms values of voltage and current corresponding to this frequency.

On the other hand, the DC capacitors are designed to limit the ripple of the DC voltage, *Voutput* in Figure 6.1(a), to around 2%. The capacitor voltage increases (or decreases) when there is active power circulation from the network to the APLC(or from the APLC to the network). The energy increment is:

$$\frac{1}{2}C\Delta V_C{}^2 = \left(P_C - P_{loss}\right)\Delta t \quad \Rightarrow \quad r = \frac{\Delta V_c}{V_c} = 0.02 ,$$

where P_C is the power incoming to the compensator and P_{loss} is the consumed APLC power. In Equation 6.1(b), *PC* has been considered constant. With an adequate control strategy, the power source supplies the load active power and the compensator losses. So, the compensator average power will be null.

The output inductance does not eliminate all no desired high frequencies of the compensation current. Besides, it is necessary to include a high-pass passive filter ,*e.g.*, a LC branch. Figure 6.1(c) shows a nonlinear compensation current flowing to the network through a LC filter and a *n:1* transformer. If the transformer relation is *n*< 1, it is possible to work with low voltages in the converter DC side.

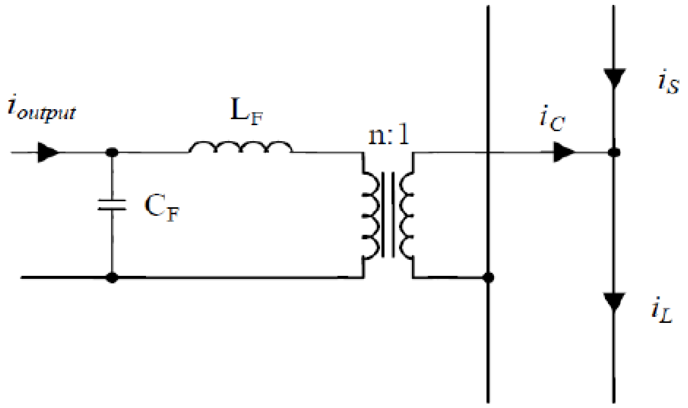


Figure 6.1(b).LC filter and network-connection transformer

For the high compensation current, the capacitor impedance, $1/C\omega$, has to be less than the inductance impedance, $L\omega$. So, these no desired components will flow to the capacitor and not to the network. The necessary L and C values to eliminate the commutation frequency component, f_C, will satisfy:

$$X_{C\,fc} << X_{L\,fc}\,.$$

If the source impedance is Z_{NET}, the equivalent impedance, referred to the APLC side, is $Z = n^2\ Z_{NET}$. This network impedance will be bigger than the L_F and C_F impedances to ensure a correct filter performance.

$$X_{C\,fc} \text{ and } X_{L\,fc} << Z$$

Figure 6.1(c) shows a general APLC output scheme, including the output inductance, the LC filter and the network impedance. The APLC output voltage isa quadrangular wave.

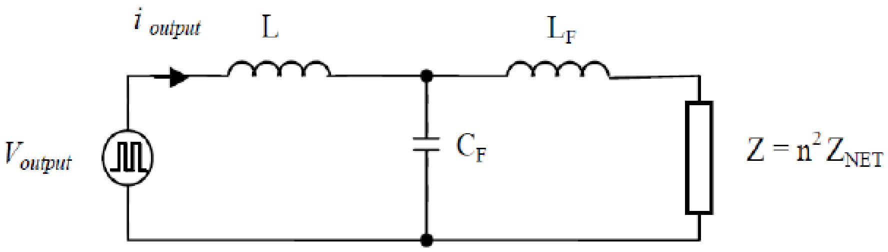


Figure 6.1(c). Equivalent scheme of a LC filter connected in the APLC output

The main waveforms are shown in Figure 6.2 to summarise the high pass filter performance.

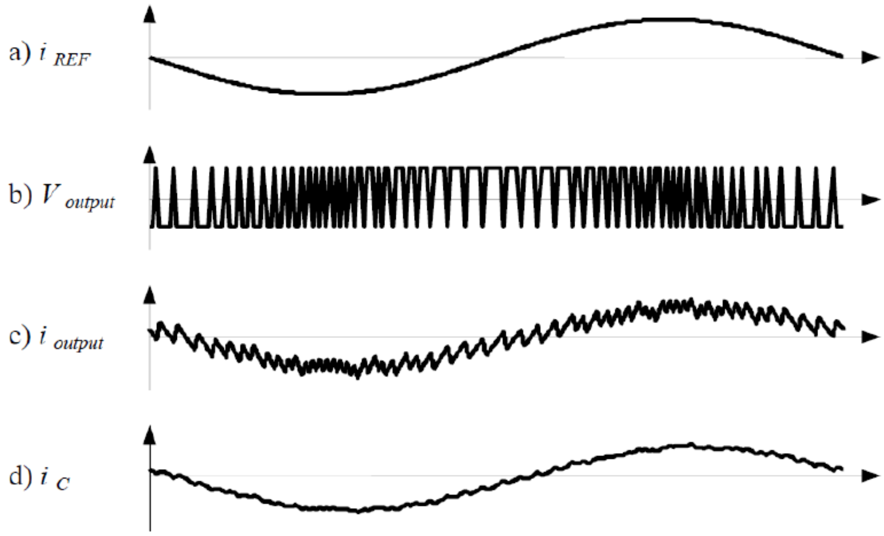


Figure 6.2.APLC output waveforms with an output inductance and a LC filter; **(a)** reference current, **(b)** output voltage, **(c)** AC output current and **(d)** compensation current

In this example, the current reference is sinusoidal, i_{REF}. The PWM control method allows the converter output voltage presented in Figure 6.2b to be obtained. The output current, i_{output}, and the final compensation current injected into the network, i_C, are presented in Figs. 6.2c, d. The quadrangular voltage is converted to a triangular current, and the LC passive filter eliminates the high frequencies.

In a practical design, it is usual to include a low resistor in series with the capacitor to limit other high-frequency currents. At these frequencies, the capacitor impedance is near to null. Besides, it is possible to place the passive LC filter in the APLC side or in the network side.

6.2 Simulation Analysis

In this section, a practical case is presented to check the shunt APLC design and their performance. The power system has been modeled in MATLAB® and Simulink® software with the Power System Blockset, including the power source, the nonlinear load and the shunt APLC, with the control and power blocks.

In Figure 6.3, a general scheme of a simulated power system is presented. The nonlinear load is an unbalanced three-phase four-wire AC regulator. The APLC control inputs are the measurements of load voltages and currents (to calculate the compensation current references according to the control strategy) and the APLC compensation currents (to implement the closed-loop current control). The APLC control outputs are the trigger signals of the power-circuit IGBTs. The APLC output current is filtered by a passive step, and the compensation current is injected into the network through a transformer. A block in Figure 6.3 represents this conditioning step.

The main source and load parameters are:

$R_1 = 52\ \Omega$, $R_2 = 52\text{x}1.2\ \Omega$, $R_3 = 52\text{x}0.8\ \Omega$; $L_1 = L_2 = L_3 = 50\ 10^{-3}$ H;

$\alpha_1 = \alpha_2 = \alpha_3 = 60°$;

$V_{source} = 230$ V, f=50 Hz.

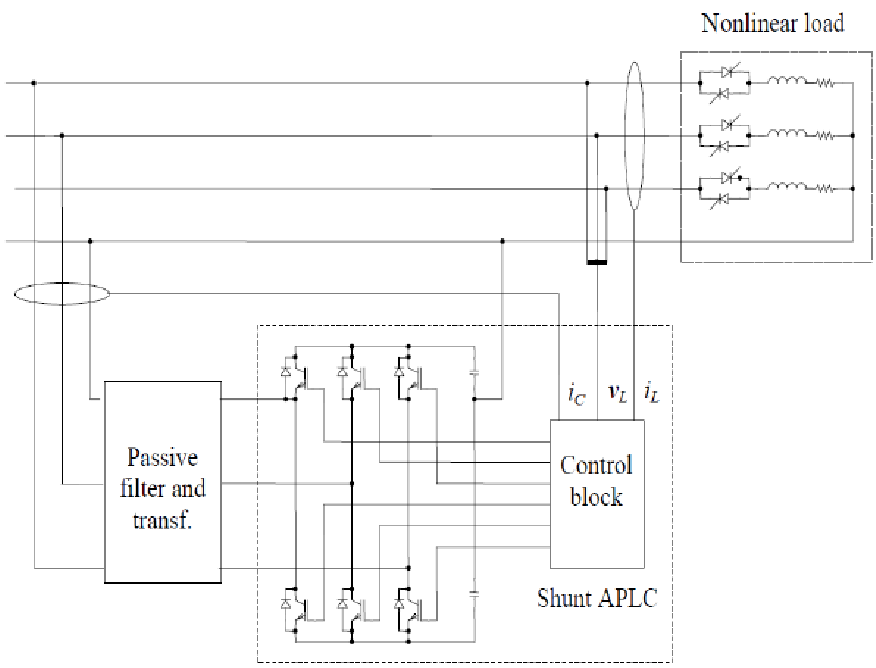


Figure 6.3. Three-phase, four-wire power system, with a nonlinear load compensated by a shunt APLC

Figure 6.4 represents the Simulink® block diagram. A circuit breaker allows switching the shunt APLC ON/OFF. The values of DC capacitors and passive filter elements are derived from Eqs.

.

C_{dc}= 2200 µF; V_{dc}= 500 V; *Transf. relation* 1:2;

L_{output}=17 mH; C_F= 20 mF; L_F= 5mH.

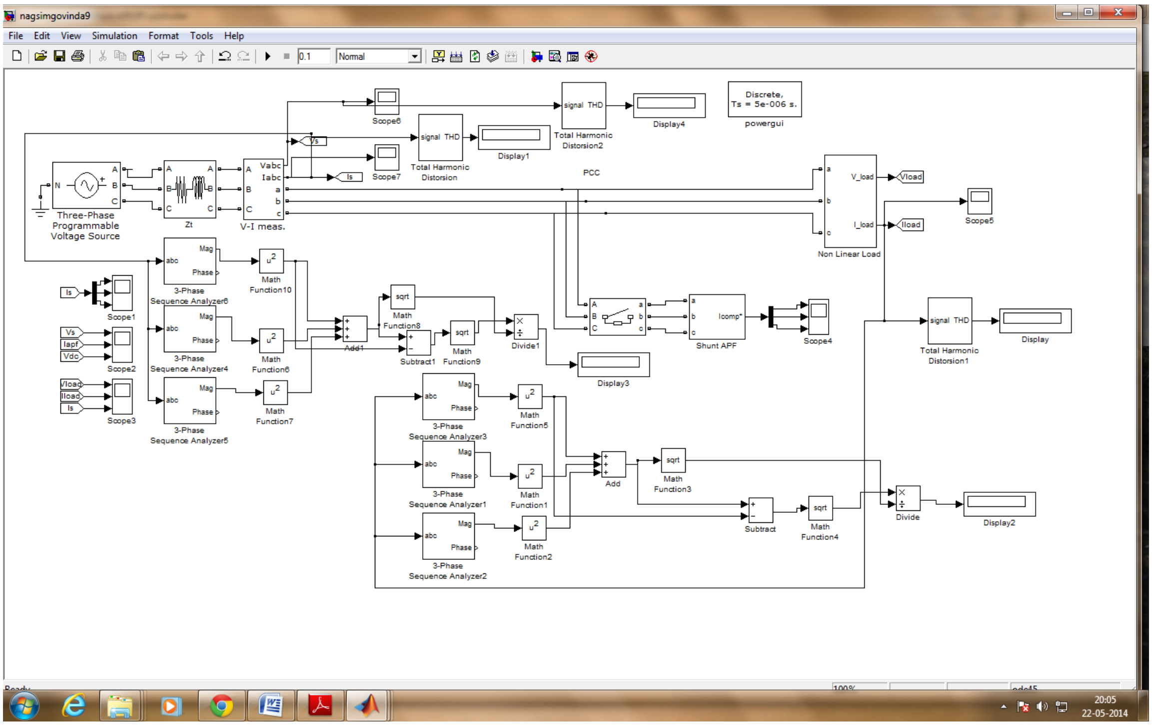
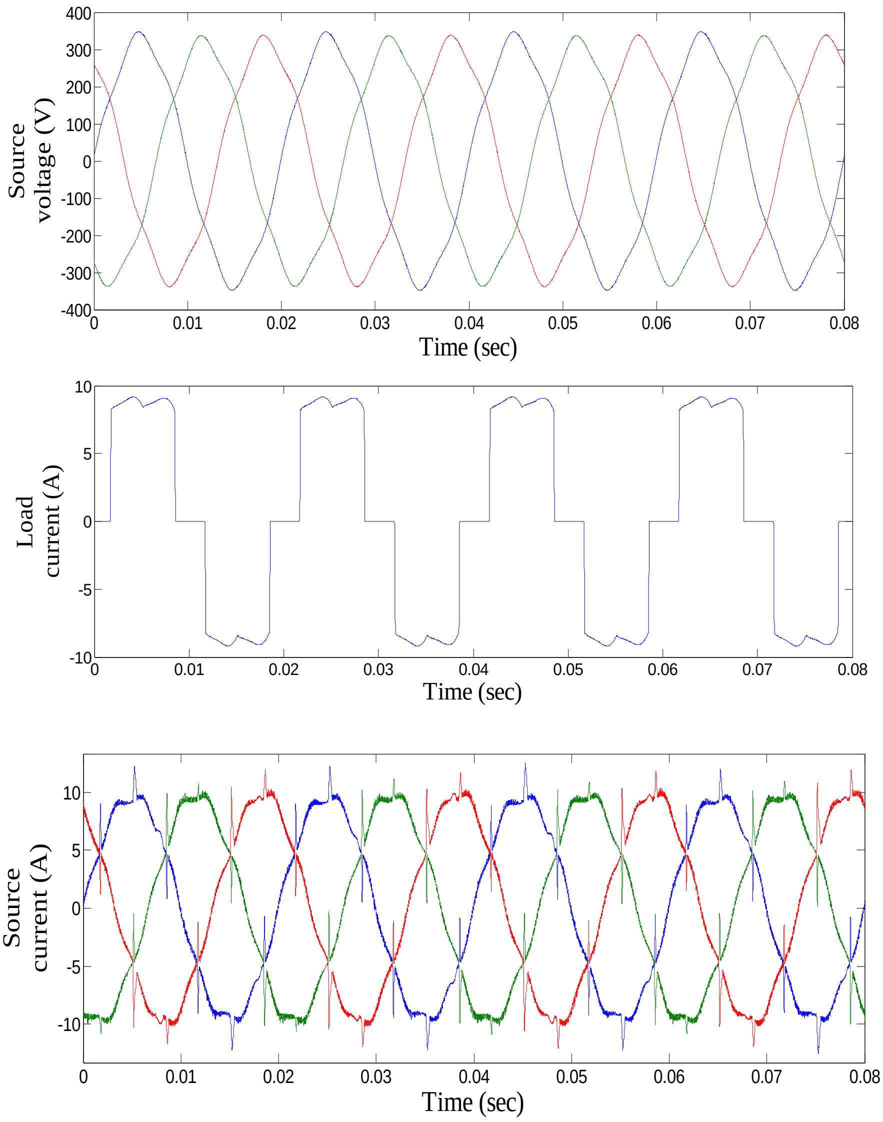


Figure 6.4. Simulink® block diagram of shunt APLC

The simulation results were obtained with the help of Matlab–Simulink Power System Toolbox software, for a distorted three phase mains voltage with shunt APLC. The proposed technique has been simulated under two cases, balanced non-linear load and unbalanced non-linear load conditions. For a three phase balanced non-sinusoidal supply system using shunt APLC both cases are investigated by detailed simulation study. The simulation results are discussed below.

6.2.1 Non-ideal source voltage simulation results with *p–q* theory:



6.2.2 Case 1: Balanced non-linear load

Fig: 6.6 shows the simulation results of the proposed algorithm under non-ideal 3-ø source voltages when balanced non-linear load is taken. The 3-øsource currents after compensation are sinusoidal, balanced and in phase with 3-ø source voltages. The instantaneous reactive power theory is feasible with self-tuning filter. After mitigation the THD and unbalance factor of supply current are minimized and are presented in Table 6.1.

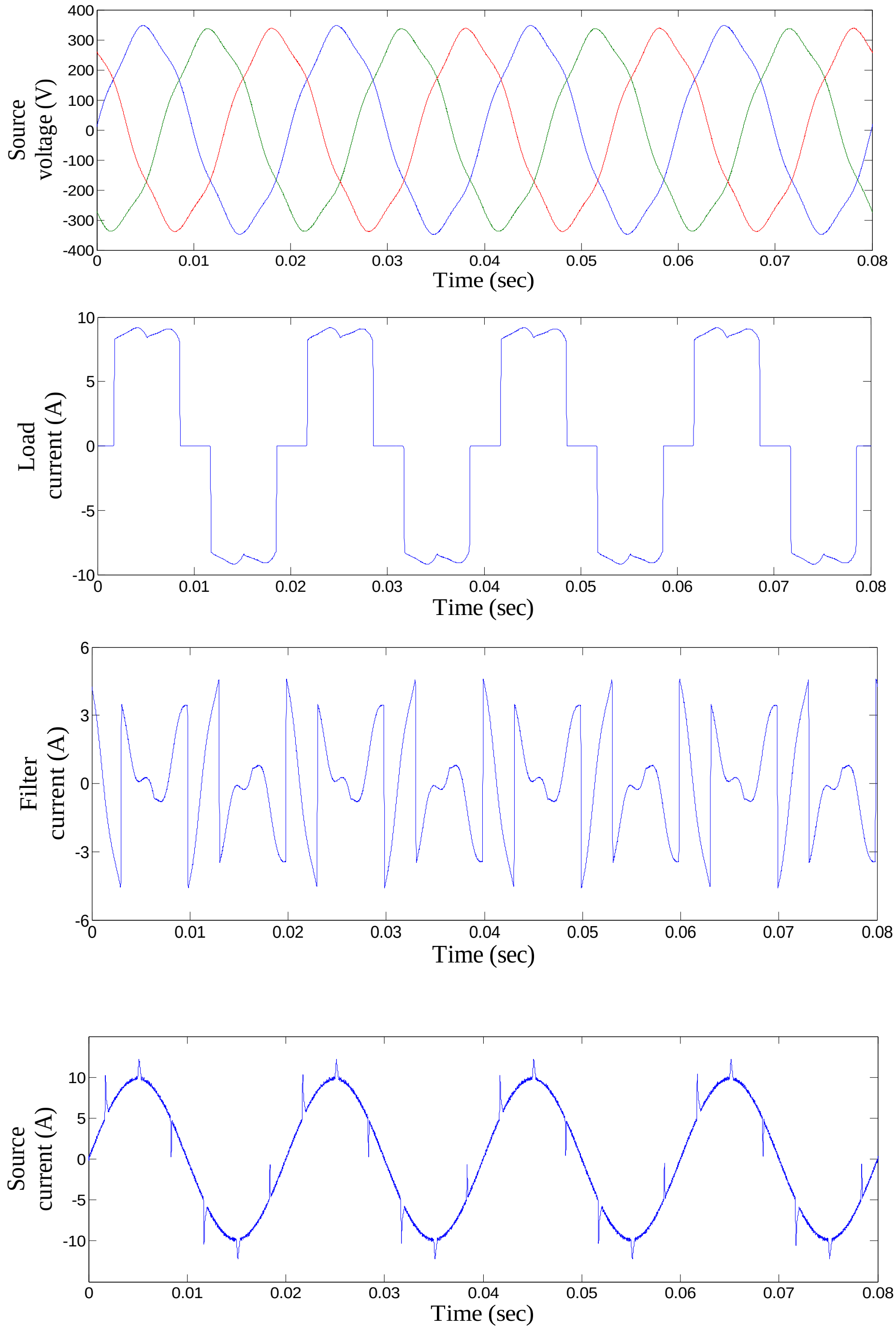


Fig: 6.6. 3-ø source voltage, load current, filter current and supply current when balanced non-linear load is connected.

6.2.3 Case 2: Unbalanced non-linear load

Fig:6.7 shows the simulation results of the proposed algorithm under non-ideal 3-ø source voltages when unbalanced non-linear load is taken. The 3-øsource currents after compensation are sinusoidal, balanced and in phase with 3-ø source voltages. The instantaneous reactive power theory is feasible with self-tuning filter. After mitigation the THD and unbalance factor of supply current are minimized and are presented in Table 6.1.

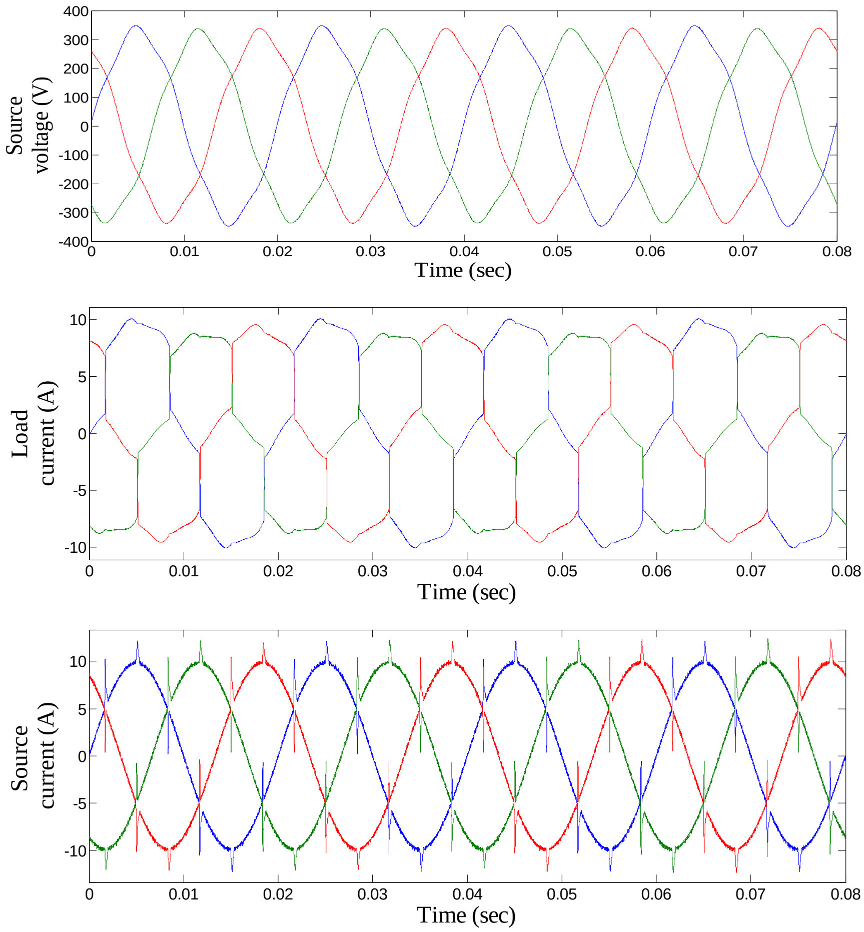


Fig: 6.7 Three phase Supply voltage, Load current, Compensating current and Supply current when unbalanced non-linear load is connected.

Table 6.1: Results with and without active power filter (apf) for *Cases*1 and 2.

	Balanced Non-linear load	***Unbalanced Non-linear load***
$I_{THD without\ apf}$	29.17%	21.04%
$I_{THD with\ apf}$	3.47%	4.64%
$I_{UNB without\ apf}$	-	5.39%
$I_{UNB with\ apf}$	-	0.76%
$PQF_{withoutapf}$	85.40%	86.70%
$PQF_{withapf}$	98.20%	97.30%

6.3 Conclusion

The case of distorted supply voltage condition has been considered. This showed the concert of the p-q theory based active power line conditioner degrades in case of non-ideal source voltage condition. The use of self-tuning filter (STF) is proposed in order to improve the harmonic suppression efficiency of APLC. Simulation results clarifies that the proposed technique can increase the performance of APLCs under non-ideal supply voltage conditions.

In this paper, a control method is presented to compensate unbalanced and harmonic currents. The shunt active power filter has been simulated and investigated for two cases i.e. for balanced and unbalanced non-linear loads. The results shows that the shunt active power filter compensated the harmonic and unbalanced components of the load current. The total harmonic distortion and unbalance factors are measured for the source current and power quality factor is derived considering the measured harmonics and unbalances of the source currents under balanced and unbalanced non-linear load conditions. The low level of harmonics and unbalances means the high level of Power quality factor. For the two cases the power quality factor has been improved.

6.4 Future Scope

- Experimental investigation can be done on shunt active power filter by designing a prototype model in the laboratory to demonstrate the simulation results for both balanced and unbalanced non-linear loads under distorted source voltage conditions.

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